Using 3D direct manipulation for real-time structural design exploration

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Acknowledgements

I would like to thank Mom, Dad, my brother, my sister, my cat...

Lund, January 2015
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Abstract

The impact of decisions on the design process is initially high and declines as the design matures. However, few computational tools are available for the early design phase; thus, an opportunity exists to create such tools. In the conventional workflow the architect uses geometric modelling tools and the engineer uses structural analysis tools in a sequential step. Parametric modeling tools are an improvement to this workflow as structural analysis plug-ins are available. This allows the architect to get structural feedback in an earlier stage, but still as a sequential step to the geometric modeling. The present work is a proposal to improve this workflow by integrating structural feedback with geometric modeling.

User interfaces of these tools needs to be needs to be interactive and agile enough to follow the designer's iterative workflow. Direct manipulation is a human-computer interaction style which enables interactive user interfaces. In this user interface style users can directly manipulate objects on the screen using real-world metaphors, which makes the users more engaged with their task and encouraged to further explorations. This is achieved through reducing the perceptual and cognitive resources required to understand and use the user interface. New technology opens up new possibilities to create new design tools that make use of very direct manipulation. These possibilities are further explored in this thesis through development of two such tools.

The first application that has been developed make use of the multi-touch of tablets. The multi-touch interface literally closed the gap between human and computer, which enables a very direct manipulation interaction for two dimensional (2D) user interfaces. The developed application is an interactive conceptual design tool with real-time structural feedback that allows the user to quickly input, and modify, structural models through the use of gestures. The second application extends these concepts and ideas into a three dimensional (3D) user interface by using a 3D input device named the Leap Motion Controller.

The present work purposes a way to integrate structural demands earlier in the design process by employing very direct manipulation user interfaces.

Keywords: Interactive structural analysis; Interactive structural form finding; 3D input device; Multi-touch user interfaces

Populärvetenskaplig sammanfattning

Det första skedet när ett byggnadsverk ska byggas är det konceptuella designskedet, det är här de första besluten om utformningen av byggnadsverket görs. I det traditionella arbetsflödet så utformas byggnadsverket först i ett ritprogram, sedan används ett annat datorverktyg för att verifiera att att det utformade byggnadsverket kan hantera de krafter som uppstår, t.ex. vind, egentyngd osv. Detta arbete är ett försök till att förbättra detta arbetsflöde genom att skapa nya verktyg som redan i ett konceptuellt designskede ger användaren en återkoppling till hur strukturen kan hantera de krafter som kommer att uppstå så att förbättringar på utformningen kan göras i ett tidigare skede.

För att skapa denna typen av verktyg så ställs höga krav på användargränssnitt, de behöver vara interaktiva och enkla att arbete med för att kunna följa designerns iterativa arbetsflöde. Direkt manipulation är en typ av användargränssnitt där användaren direkt kan manipulera objekt på skärmen. Denna typen av användargränssnitt skapar intuitiva gränssnitt som är enkla att förstå och som uppmanar användaren att experimentera och utforska möjligheter. Ny teknik skapar nya möjligheter att skapa nya designverktyg för konceptuell design som använder en sådan, väldigt direkt, gränssnittstil. Dessa nya möjligheter utforskas vidare i denna avhandling genom att utveckla två olika designverktyg.

Det första av dessa verktyg tillåter väldigt direkt manipulation för ett två-dimensionellt (2D) användargränssnitt genom att utnyttja moderna pekskärmar. I det utvecklade verktyget kan användaren enkelt mata in och manipulera modeller genom att använda pekskärmen. Användaren presenteras med resultat från strukturberäkningar i real-tid, vilket tillåter användaren att experimentera och utforska nya former. Det andra verktyget som har utvecklats vidareutvecklar dessa koncept och idéer till tredimensioner (3D) genom att använda en ny sorts 3D input enhet, som heter Leap Motion.

Resultatet från detta arbetet är ett förslag på hur verktyg för konceptuell design kan förbättras genom att interagera strukturella aspekter, detta sker med hjälp av väldigt direkta användargränssnitt.

Contents

Part I

Introduction and overview of the work

1 Introduction

1.1 THE STRUCTURAL DESIGN PROCESS

Before a new building or structure can be built it needs to be designed. This design phase, here termed *structural design phase*, is a very important step of the building process. The total cost for the structure, energy performance, structural performance etc. are largely dependent on the result of the structural design process.

The structural design process is never a straightforward procedure. Rather, solutions are reached through an iterative, and often chaotic process. The process can be divided in to the four following steps [1]:

1. **Conceiving**: The most important design step where the overall design concept and significant details are developed.
2. **Modeling**: Idealization and simplification of the structural design concept, building of models for structural analysis and calculation of forces.
3. **Dimensioning**: Deciding sectional dimensions of structural members depending on the choice of materials.
4. **Detailing**: Final details of nodes and connections including the creation of construction documents.

In reality there is not necessarily a clear distinction between the different design steps and the process can iteratively move forward and backwards until a solution is reached. In this thesis the term conceptual design refers to the first design step conceiving and the initial phase of the modeling step. In the initial design phase the design freedom is considerable. At the same time the impact on the final result of the of the decisions taken at this early stage are often crucial. In contrast, both the design knowledge and the availability of design tools increases as the design matures during the later design stages [2,3], see Figure 1.1 and Figure 1.2. The design knowledge comprises of all that is known of the final design, from color of

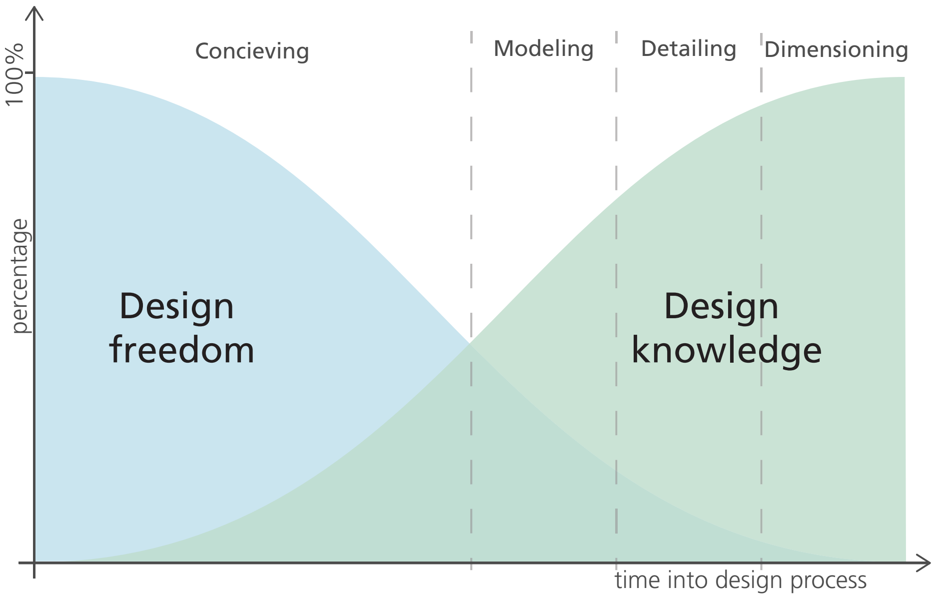

Figure 1.1: Structural design process [2]

the facade to dimensions of structural members. The lack of tools for the initial design phase combined with the high impact of decisions creates an opportunity to develop such tools. Tools that can support the designer to make well informed decisions in the conceptual design phase.

1.2 PROBLEM STATEMENT

Many different geometric modeling tools are today available for architects. These geometric modeling tools have, since their introduction in the 1980s, grown increasingly sophisticated. They have also, together with the widespread perception of the benefits of technological innovation, created a more intimate relationship between technology and design. This relationship has resulted in parametric design and scripting methods that can generate complex shapes and forms [4]. The distinct separation found in practice where architect's use geometric modeling tools and engineers use analysis tools further reinforces the architects role as *form-giver* and the engineer as *form-verifier* [5]. To move away from this separation, when the term *designer* is used in this thesis it represents either an engineer or an architect. Instead of the current practice, it would be beneficial if the engineer and architect would collaborate as designers in the structural design process. This would allow physical demands to work as an inspiration, rather than as a constraint of what is possible, to find new well performing geometric forms. Where physical demands can for example be: structural performance, construction costs, operational energy

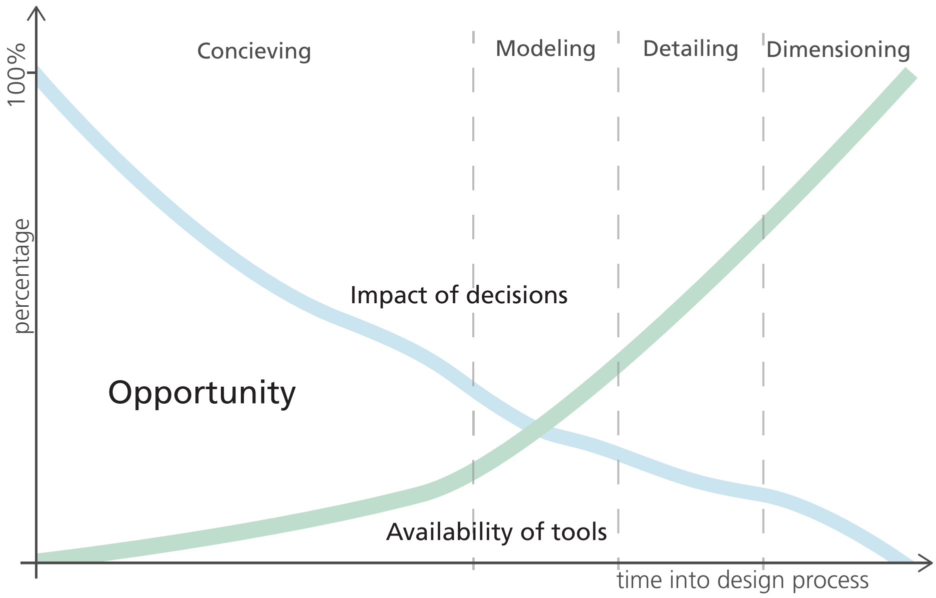

Figure 1.2: Impact of decisions and availability of tools in the design process [3]

needs, acoustics.

In the current practice the architect often conceives a design without involvement of the structural engineer. Hence, the importance of the conceptual design phase is often overlooked and structural aspects are often only considered in a late design stage [6]. A contributing factor to this is that very few computational tools are available for conceptual design.

The challenge when developing such computational tools lies within the fuzzy nature of the problem, knowledge and constraints of the problem are imprecise and incomplete [3].

Conventional advanced structural analysis software requires precise knowledge of the problem and is insufficiently agile to follow a designer's iterative workflow. Conventional structural analysis software is developed for use in the late design stage, when the major design decisions have been made, as a tool for the engineer to verify the form.

A subsequent problem with the traditional workflow, where the architect is the form-giver and the engineer is the from-verifier, can arise due to the availability of the a very detailed geometric model. It can be tempting for the engineer to directly perform a full analysis on the detailed geometry something which is possible with today's structural analysis software. If instead the engineer starts with a simple mathematical model and then gradually increases the complexity - known as hierarchical modeling, see Figure 1.3 – the risk of fatal mistakes is decreased [7].

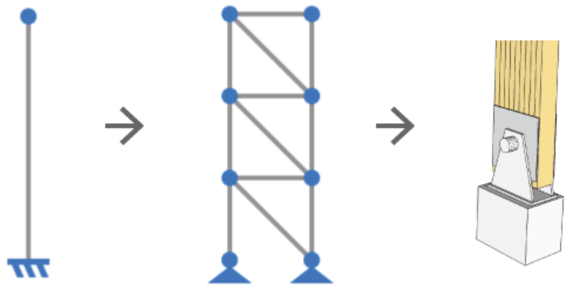

Figure 1.3: Hierarchical modeling

By starting with a simple mathematical model the engineer can focus on, and get a better understanding of, the overall structural behavior. Where the overall structural behavior is how stresses follow through the structure, what the magnitude of the stresses are in different structural members, etc. This information can be valuable when a more advanced mathematical model is used, to confirm the feasibility of the results. It has been shown that premature use of advanced structural analysis software negatively affects the conceptual understanding and the quality of the conceptual design [8].

In the present work, two similar computational conceptual design tools have been developed. The two applications make use of simple mathematical models, which enables structural modeling to be used earlier in the structural design process. The motivation for this is two-fold. It can give the designer valuable feedback on structural performance in the conceiving phase, when the impact of decision still is high. And it can also give the engineer valuable feedback on structural behavior before a more advanced model is used.

The type of design tool that is used to generate and represent ideas also affects the quality and quantity of early prototypes. It was shown in [9] that physical prototyping generated a higher quantity of prototypes, compared to using CAD or conventional sketching, under the same amount of time. The prototypes that were developed using physical prototyping were also perceived as more novel compared to the other prototypes. However, the prototypes that were perceived as more novel also tended to fare poorly on all other measureable qualities [9].

In the present work the prototypes are structural models. As computational models are used, a measurable performance can be computed and presented to the user in real-time. This can potentially can improve the quality of the structural models. The measureable performance and guidance in the present work put emphasis on the geometrical form of the structure as this has the greatest potential to improve the structural performance [10].

Figure 1.4: Pierre Luigi Nervi - Air hangar, built 1936

1.2.1 Examples of well-executed conceptual structural design

Structural demands can be integrated earlier in the design process by using them as inspiration of geometric forms instead of constraints of what is possible. Integrating structural demands earlier in the design process have the potential to reduce the amount of material needed, reduce environmental impact and lower costs for the project as a whole [2].

A good example of well-executed conceptual designs are the structures designed by the Italian architect-engineer Pierre Luigi Nervi, see example in Figure 1.4. Despite the complexity of his structures his designs were often selected because they were the cheapest to build [11], as less material was needed for his designs compared to his competitors. This type of complex concrete structure is unfeasible when labor costs are high, due to the extensive formwork required [12]. However, This is something which could of course change in the future with the emergence of robots and digital manufacturing [13].

"His buildings are most remarkable for the clarity of their engineering. The power and grace of these extraordinary shapes and patterns stems directly from their structural logic, and are inseparable from it" – Ada Louise about Pierre Luigi Nervi, 1960 [2]

The Shenzhen CITIC Financial Center, see Figure 1.5, is a more recent example of

Figure 1.5: Shenzen CITIC Financial Center, Lead Architectural Partner: Craig W. Hartman, Lead Structural Partner: Mark Sarkisian. Rendering © Skidmore, Owings & Merrill LLP, 2016

well-executed integrated conceptual design. The perimeter frames are inspired by research on optimal discrete truss geometries to minimize the material needed [14].

Designing Nervi's air hangar in 1936 required a very thorough understanding of structural mechanics. He was at the time the only one, or one of very few engineers that was capable of successfully designing such a structure. The CITIC Financial center was also designed by a team distinguished designers. The difference between the two examples are that the latter used computer computations in the design process.

1.2.2 Computational design tools

Computational design tools have the possibility make computer computations readily available in the design process, to help guide the designer towards well-performing solutions. Such tools have previously been developed and a review of existing tools and the methods that they implement are available in Chapter 3. These tools are developed to follow the designer's iterative workflow, which the conventional structural analysis software lacks.

Allowing these computational tools to follow the designer's iterative workflow puts high demand on the user interface of the tools. Most of the existing computational design tools are developed for mouse and keyboard input. In the present work alternative input devices are explored, which allows for a more direct input.

1.3 RESEARCH METHODOLOGY

1.3.1 Aim of research

The long term goal with this research is to improve the conceptual design phase by integrating structural demands early in the design process. An improved conceptual design phase has the potential to improve the quality of structures in the built environment. These qualities can for example be: structural performance, construction costs, operational energy needs, acoustics.

- To improve conceptual structural design by developing computational tools that bridge the gap between the design steps conceiving and modeling.
- To create intuitive conceptual structural design tools that allow the user to easily explore different design alternatives.
- To improve the human-computer interaction for such tools though use of new, novel user input devices.

1.3.2 Research questions

- How can the human-computer interaction be improved in computational conceptual structural design tools?
- Which computational methods can be used to improve the conceptual design phase?

1.3.3 Research approach and limitations

The present research is a multi-disciplinary work between structural mechanics, computer science and architecture. Methods from structural mechanics are used to provide the user with guidance and feedback. Developing user interfaces and employing programming techniques is a part of the computer science discipline. Studying conceptual design and finding geometrical forms are a part of architecture. The research is applied and any successful tools that this work results in could potentially be used in practice with few changes.

There are different research approaches to investigate how the conceptual structural design phase can be improved. In this work, it has only been investigated how new computational tools can improve the conceptual design phase. Project management, social aspects and culture is not considered in this work.

Many different computational methods exist that can be used for conceptual structural design. Some promising methods are presented in Chapter 3, a selection of these methods have been used in the present work.

1.3.4 Outline

Part I is an introduction to the research area and also literature review of previous work in this field. This part is similar to, but an extension of, the introductory sections in the appended papers. **Chapter 1**, is an introduction to the research area, and motivates why this work is important. **Chapter 2** introduces human-computer interaction to the reader and introduces state of the art technology, such as new input devices. **Chapter 3** , presents computational methods that can be applied to conceptual design. Different optimization methods, especially the genetic algorithm, are thoroughly introduced; as these methods will be used in future work. **Chapter 4** reviews existing conceptual structural design tools. In **Chapter 5** requirements for integrating structural feedback in the conceptual design are presented, and a summary of the present work is presented. The publications that this work has resulted in are presented in **Chapter 6** and **Chapter 7** summarizes the present work and the intellectual contributions. **Part II** is appended publications.

2 Human-computer interaction

Human-computer interaction is a multi-disciplinary research area that includes: user interface design, hardware, software, social aspects and more. Important concepts in this research area are usability and user experience.

With new technology such as novel input devices and increased computational power comes new possibilities. The present work makes use of these new possibilities. Novel user input devices are used for structural modeling, and increased computational power is used for real-time structural analysis.

2.1 DIRECT MANIPULATION

Direct manipulation is a human-computer interaction style with continuous representation of objects of interest with rapid, reversible and incremental feedback [15]. Users can directly manipulate objects on the screen using real-world metaphors, which makes the users more engaged with their task and encouraged to further explorations [16]. This is achieved through reducing the perceptual and cognitive resources required to understand and use the user interface [17].

2.2 VISUALIZATIONS

Scientific visualization is a subfield of computer graphics. The purpose of scientific visualizations is to graphically illustrate scientific data. This is also important for any conceptual structural design software to be successful, how the result is visualized is of great importance. The result should be visualized in a way so that the user quickly can interpret the result and gain insight from it.

In Figure 2.1 is an example of how the result from a computational analysis often is performed. The original geometry, an undeformed car, is modified with the computed displacement. The geometry, in this case the car, is also colored according

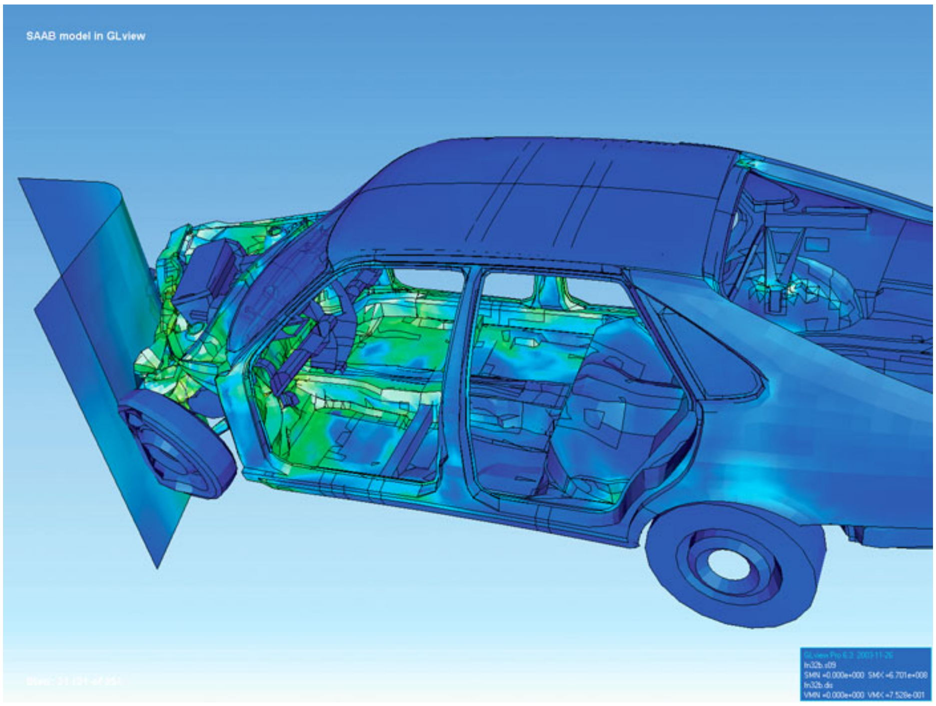

Figure 2.1: Visualization of how a car deforms in an asymmetrical crash using finite element analysis.

to some selected condition. The color can for example represent von Mises tensions, shear forces, bending moment etc.

Edward Tufte is one of the pioneers in the field of data visualization with his books on information design [18–20]. He has in [20] written a few principles of graphical excellence which he stated as follows:

- Graphical excellence is the well-designed presentation of interesting data – a matter of substance, of statistics and design.
- Graphical excellence consists of complex ideas communicated with clarity, precision and efficiency.
- Graphical excellence in that which gives to the viewer the greatest number of ideas in the shortest time with the least ink in the smallest space.

2.3 TECHNOLOGY

The introduction of different input devices such as the mouse and joystick significantly improved the human-computer interaction of user interfaces that adapted accordingly [17]. When the touch screen was introduced it had an advantage over all these devices. The user could literally touch objects on the screen to manipulate them, creating a very direct method of inputting information[17]. This closed the gap between the human and the computer.

There is a wide repertoire of interaction techniques to create direct manipulation user interfaces for three-dimensional (3D) applications using two-dimensional (2D) input devices such as the mouse [21]. However, since this type of input devices have one degree of freedom less than the 3D user interface there will always exist a need of gestures or similar methods.

The Leap Motion controller [22], is a relatively small and simple input device that is placed in front of the users keyboard, it then tracks the users hands that are in the controllers field of vision. Combined with the software development kit (SDK), the controller creates a computational model of the users hands, which can then be used to interact with software in 3D. This enables very direct manipulations for 3D user interfaces.

Computer games have seen an increase in the amount of novel input devices along with a new style of games to address some limitations of conventional systems [23], e.g. the Wii remote [24], Microsoft's Kinect for Xbox [25] and PlayStation Move [26]. These novel input devices move away from the conventional human-computer interaction to invoke an intuitive interaction that supports the natural human way of working. Games have for long been perceived as fun and engaging, and it has been investigated in many different disciplines if gaming methods can improve the human-computer interaction. In order to create more effective, immersive and engaging learning or training [23].

Interest for and development of virtual reality glasses have recently increased, and products such as the Oculus Rift [27] and PlayStation's Project Morpheus [28], have recently become widely available. This type of virtual reality glasses has primarily been developed for games but other fields have also shown interest, e.g. in [29] a virtual reality is used to help students understand complex structural behavior.

3 Computational methods

In this section a number of computational methods that can be used for conceptual structural design are introduced.

3.1 FORM FINDING

Physical models or numerical simulations can be used for form finding, where the aim is to find the form for a structure under load where static equilibrium is satisfied. The static equilibrium corresponds to a structure that can support the applied load using only compression or tension, thus a very efficient structure. For physical models a hanging chain or cloth can be used the find the static equilibrium.

A number of different form finding methods exists, and they can be divided into three major categories [30]:

- Stiffness matrix methods - which are based on elastic and geometric stiffness matrices. These methods have adapted methods structural analysis for form finding.
- Geometric stiffness methods - these methods are material independent. The first such example is the force density method [31] which makes use of the ratio of force to length. Several other methods have been developed which extends on this work.
- Dynamic equilibrium methods - these methods find the steady-state equilibrium through use of dynamics. One such method is dynamic relaxation [32] which is explained in further detail in Section 3.1.1.

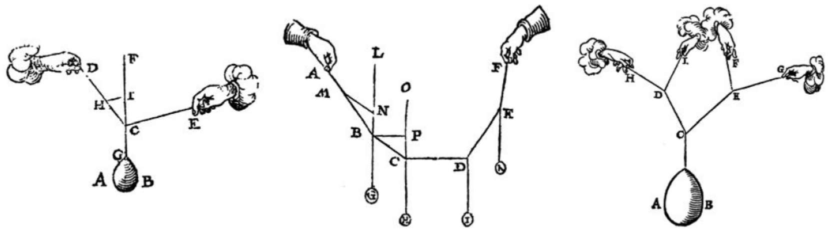

Figure 3.1: Funicular shapes by Stevin (1586)

3.1.1 Dynamic relaxation

Dynamic relaxation is a method to solve a set of non-linear equations. The method computes the movement of a structure over time to find static equilibrium between the internal and external forces [32,33].

In each time step, Δt, for all elements are computed from the nodal displacements u. A residual, R, can be computed by using

$$R = f_{ext} - F_{int}$$

Where f_{ext} is the external forces acting on the structure. By using Newton's second law the acceleration (time derivative of the velocity) can be computed as follows (at the node i, in the x-direction, at the time t)

$$R_{ix}^{t} = M_i \cdot \dot{v}_{ix}^{t}$$

is a lumped, fictitious mass at node i. To enforce boundary conditions, the residual is set to zero for the corresponding degrees of freedom. With the time step known the velocity of node i in the x-direction can be computed using finite difference method

$$v_{ix}^{t+\Delta t} = v_{ix}^{t-\Delta t} + \frac{\Delta t}{M_i} \cdot R_{ix}^{t}$$

With the velocity known the updated geometry can now be updated by using

$$x_{ix}^{t+\Delta t} = x_i^{t} + \Delta t \cdot v_{ix}^{t-\Delta t/2}$$

As the geometry is updated, an iteration is complete and the computations start over, by again, computing the residual. The geometry is modified in each iteration until equilibrium between external and internal forces has been reached. Viscous or kinetic damping is often used in order for the method to converge [33].

A recent development is a formulation that combines CAD-geometry and dynamic relaxation [34] for form-finding.

3.2 OPTIMIZATION METHODS

Michell was a pioneer in the field of structural optimization [35] when he in 1904 published his results with minimum-weight Michell trusses. These trusses are still used today as benchmarks for topology optimization with framed trusses [36].

Structural optimization is a numerical method to find the best solution for a mathematically formulated objective function that is subject to a set of constraints. The following variables are always present in structural optimization [37]:

- *Objective function (f)* - A function to classify designs from a quantifiable objective, the function returns a numerical value that represents how good the design is out of one or more criteria. Usually a small number is better then a large, i.e. a minimization problem. Frequently f measures weight, maximum displacements, strain energy or cost.
- *Design variable (x)* – A vector that describes the design with numerical values, it often represents a topology, nodal positions, cross sectional area or material.
- *State variable (y)* – For a given design with the design vector x, y represents the response of the structure i.e. how well the structure is performing from the evaluated criterion.

The optimization problem can now be described as follows [37] :

$$SO = \begin{cases} \text{minimize } f(x,y) \text{ with resepct to } x \text{ and } y \\ \text{subject to} \begin{cases} \text{behavioral constraints on } y \\ \text{design constraints on } x \\ \text{equilibrium constraints} \end{cases} \end{cases} \tag{3.1}$$

A number of different numerical methods exist to perform the optimization, and the best method depends on the solution space for the problem. A problem can also have multiple objective functions, so called multi-objective optimization. Which can be formulated as follows:

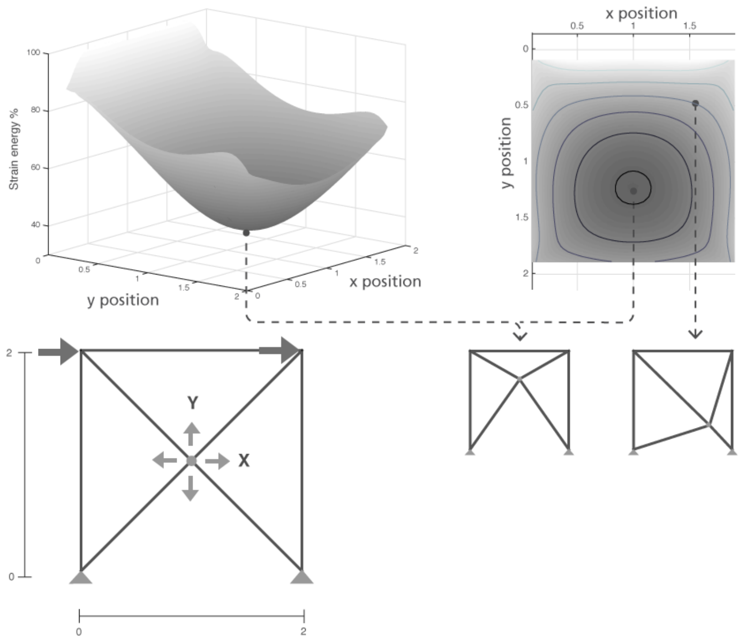

Figure 3.2: Design space for a shape optimization problem

$$minimize(f_1(x, y), f_2(x, y), \ldots, f_n(x, y))$$

This is not a standard optimization problem as the objective functions are optimized for the same design variables. Instead a so-called Pareto optimality is sought, where there is no other design that satisfies all the objectives better [37]. If no single Pareto optimal point exists instead a Pareto front can be found in the objective space, where the objective space is a space with the different objectives on the axis. The objects can for example be, structural efficiency, operational energy consumption, sunlight etc.

3.2.1 Gradient based methods

Gradient-based methods make use of the first, and some the second, derivative to iteratively converge towards a solution. These types of methods are fast, consistent and the result is repeatable (no randomness). However, the solution space of the objective function needs to be convex (such as the design space in Figure 3.2), continuous and at least once differentiable. The problem with using this type of methods for engineering and design, is that the problems are often so-called messy problems [1], that is non-convex solution spaces that contain multiple local optima.

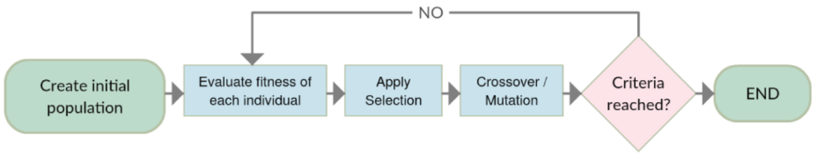

Figure 3.3: Genetic Algorithm procedure

Examples of gradient-based methods are steepest descent and Newton-Rhapson [37].

3.2.2 Evolutionary algorithms

Evolutionary algorithms are a collection of generic population-based heuristic optimization algorithms [38]. The algorithms are inspired by biological evolution, survival of the fittest and natural selection. The solvers introduce randomness to search the solution space, which improves the algorithms ability to find the global optima.

One of the most well-known and used algorithms in this category is named genetic algorithm [39], it is inspired by the biological evolution. The benefits of this algorithm are that it is very robust and always returns a solution and the objective function does not need to be differentiable.

The procedure for genetic algorithm can be described as follows, see Figure 3.3:

1. *Create initial population* – First an initial population is created, either on random or through some type of sampling (e.g. Latin hyper sampling [40]).
2. *Evaluate fitness of each individual* – The objective function is called which gives each individual a score (heuristic).
3. *Apply selection* – The individuals with a high fitness score have a higher chance to by selected for crossover, a biological metaphor for mating.
4. *Crossover/Mutation* – The individuals with a high fitness recombine properties (in this context design variables) with each other, to create a new generation. Introducing a small chance of mutation, a random change, when two individuals crossover can minimize the risk of the algorithm to get trapped in local optima. Elitism can be introduced to always allow the best performing individuals to move to the next generation, which can improve convergence.
5. *End* – The procedure continues until a preselected criterion is reached, often number of generations or when solution stops to converge.

A weakness of genetic algorithm is that it can be very computationally heavy, as the objective function needs to be called for each new individual. There is also a lot of fine tuning, different types and rates of crossovers, mutations etc.

A strength of the algorithm is that multiple well performing solutions can be presented fore the user (different individuals from the population). This can be used in conceptual design, where an aesthetically attractive well-performing solution is sought. The algorithm can also be used for interactive optimization [41], where a user can intervene the selection process to move the population in a desired direction. The algorithm has also been adjusted for use with multiple objective optimization, where the population converges to the Pareto front [42].

3.2.3 Topology optimization

To optimize the material layout, given a set of boundary conditions and external forces, topology optimization can be used. The method can be implemented through the use of finite element analysis combined with optimization methods [43]. However, the resulting optimal material layout can be infeasible to build due to high complexity.

3.3 EIGENVALUE ANALYSIS

Eigenvalue analysis can be used to find the dynamic or static modal shapes for a structural model. From the stiffness matrix K of a structure, a set of scalar stiffness values can be determined [44]. Assume that a set of displacements a exists, that are proportional to a corresponding set of forces f, i.e.

$$\mathbf{f} = \lambda \mathbf{a}$$

This can be combined with a linear elastic finite element formulation, i.e.

$$\mathbf{K}\mathbf{a} = \mathbf{f} = \lambda \mathbf{a}$$

Which can be rewritten as

$$(\mathbf{K} - \lambda \mathbf{I})\mathbf{a} = 0$$

This is a standard eigenproblem. The eigenvalues λ have the unit force/length, also called canonical stiffness values [45]. Every eigenvalue λ_i has a corresponding eigenvector $\mathbf{a_i}$, which describes a modal shape. Eigenvalues equal to zero means zero energy is required to form the corresponding modal shape, i.e. a rigid body motion. The eigenvectors are only defined within a scalar multiple. To create an animation of the modal shape, the eigenvector can be normalized and multiplied with a positive and negative scalar. This result in two different shapes, interpolation between the two shapes can then be used to create an animation.

3.4 GRAPHIC STATICS

Graphic statics is a graphical method to find funicular shapes and compute forces for structural models through the use of a force diagram. The method was first published in 1886 by Karl Culmann [46], the method was widely used until the 1970s, when the increase in computational power made numerical simulations widely available.

The method has recently gained attention from the research community [12,47,48] because of its simplicity and power. However, the method is limited to statically determinate problems with axially loaded members.

4 Literature review

4.1 ANALYSIS-BASED TOOLS FOR ENGINEERS

The development of finite element analysis (FEA) has resulted in many different, but very similar, software analysis tools. These tools are often too complex and not agile enough to be used for conceptual design. Their use requires a high level of skills both in connection with the software and in engineering terms. This type of software has been developed for the late design stage as a tool for the engineer to verify the form.

The analysis procedure for this type of software is often a step-by-step workflow, where all the steps need to be completed in order before the analysis is carried out, see Figure 4.1. The user experience has been compromised by this step-by-step evolution.

4.2 GEOMETRY-BASED TOOLS FOR ARCHITECTS

4.2.1 History

The first computer-aided design (CAD) tool, termed Sketchpad [49], was developed by Ivan Sutherland at MIT in 1963. The revolutionary feature of Sketchpad was real-time representation of the geometry on the display, which could be modified with the use of a new input device, a light pen. The light pen enabled a complete interaction loop between the computer and the designer. The software had support for complex relationships between graphical elements; for example, a line could be

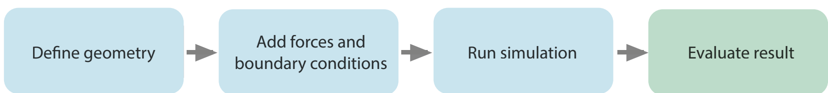

Figure 4.1: Conventional simulation cycle

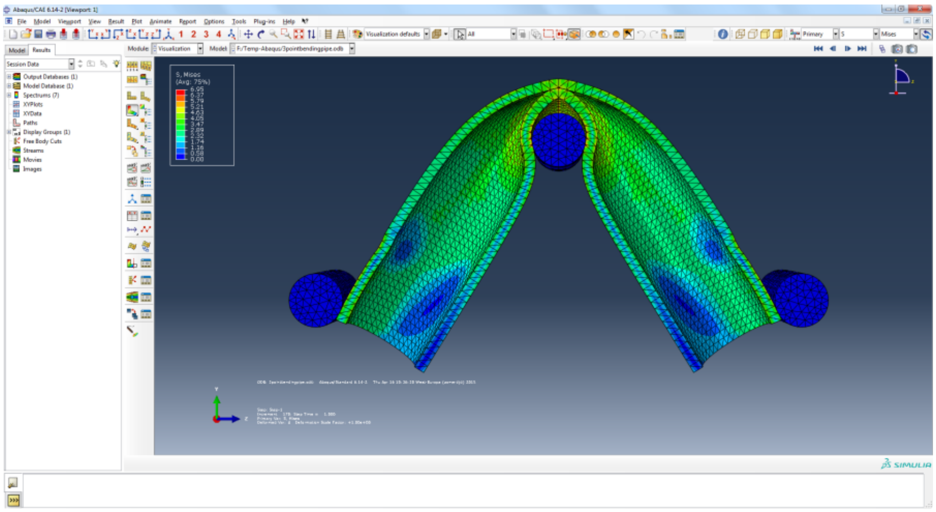

Figure 4.2: User interface of conventional analysis software (ABAQUS)

Figure 4.3: Sketchpad - the first CAD tool

defined by relationship to other graphical objects, perpendicular to, parallel to, same length etc. Sutherland had a vision that the designer would first create a rough sketch of the design. And then, as the design matured, apply constraints to the graphical objects to get a more detailed and precise design.

Computer aided design tools, 2D drafting tools, were first affordable and accessible to a wider audience in the 1980s [49]. The succeeding 2D drafting software unfortunately failed to capture Sutherland's original intentions of using the computer as a creative design tool, by not including the constraint model.

4.2.2 Present day

As mentioned earlier, many different geometric modeling tools are today available for designers, such as parametric modelers. These parametric modelers have successfully captured some of Sutherland's ideas of constraint models.

The software Rhinoceros 3D [50], which is a NURBS modeler, can be combined with the plug-in Grasshopper [51], that enables a visual programming environment. The software developer company Autodesk has also launched a parametric modeling tool named Dynamo [52] that has similar features.

In Grasshopper the designer can connect a slider to a parameter - for example the width or curvature of a model – the geometry then updates in real-time as sliders are manipulated. This enables complex shapes and forms to be generated and manipulated, allowing the designer to explore the parametric design space.

Many plug-ins also exist for Grasshopper, and these can be combined with each other, one such example is Karamba [53], which enables structural performance feedback within the parametric modeler.

4.3 EXISTING CONCEPTUAL DESIGN TOOLS

"Geometry and algorithms can exist in the abstract, but to be of any practical significance, to become a design tool which can be used by designers, then these have to be encapsulated in an executable form, as working software..." - Robert Aish [54]

A number of different conceptual design tools exist; they have here been divided into categories depending on the computational methods that they make use of.

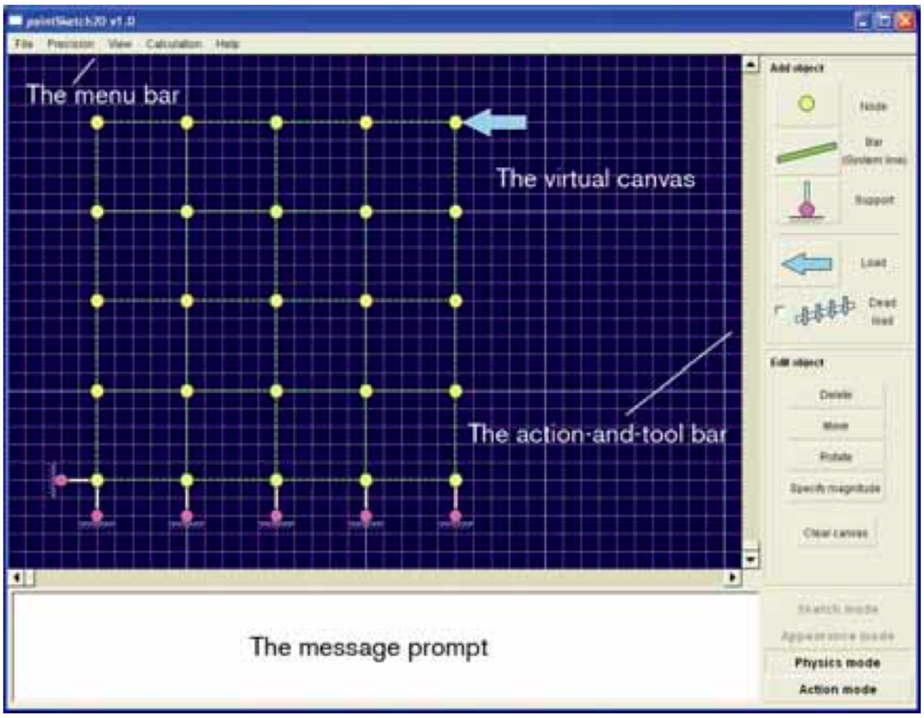

Figure 4.4: The software tool PointSketch

4.3.1 Real-time analysis tools

This type of conceptual design tools makes use of simple mathematical models to provide the user real-time feedback from structural analysis. Various such tools have previously been developed, the first two such tools were developed in parallel and released in 2006, named Pointsketch [45] (see Figure 4.4) and Arcade [55]. In the two different software tools, the user can create a structural model using mouse and keyboard input. Forces can then be applied to the model and the results are visualized in real-time

The first tools were developed in academia but industry has shown interest in the concept. Autodesk launched a new application in 2011 named ForceEffect [56], which is available both as an tablet and as a web application. The application is developed for designers to analyze and visualize two-dimensional truss structures. The tablet application utilizes a direct manipulation user interface style where the user can make changes to the model by directly touching the objects. The commercial finite element (FE) software SAP2000 [57] launched in 2012 a model alive feature, this feature enables real-time feedback with deformations and forces for truss-structures [58].

Recently an interactive physics engine was developed to create a user experience

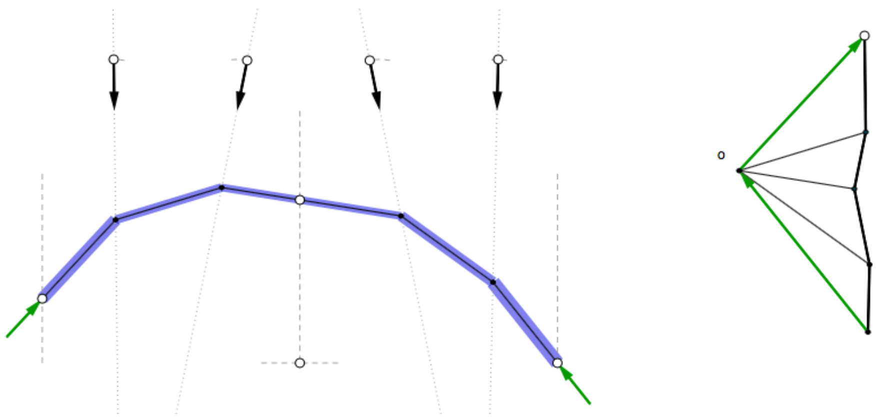

Figure 4.5: The interactive graphic statics software Equilibrium [47]

inspired by games for design and education [59]. The developed physics engine has been used to create an interactive game called Catastrophe, which aims to teach users which elements are critical to system stability through play.

4.3.2 Graphic statics tools

Multiple graphic static computational design tools have been developed; they make use of graphic statics simplicity that allows the computations to run in real-time. The first such application that was developed such application is ActiveStatics [60], a web-based tool that allows the user to explore graphic statics. Focus of the tool is teaching how graphic statics works, and extensive examples are available. A very similar version named Equilibrium [47] was later developed, see Figure 4.5. Another similar design tool that instead makes use of particle-spring system for computations is CADenary [61].

4.3.3 Interactive optimization design tools

Genetic algorithm can easily be used for interactive optimization, where the user can intervene the selection process and direct the population in a desired direction. Such applications have been developed for conceptual structural design, to generate and analyze structures such as bridges and trusses. One such tool is von Buelow's interactive evolutionary design tool [62], which has support for both 2D and 3D structures.

Another similar application, developed as a web application, is named StructureFIT [63,64], see Figure 4.6. The software tool also has a direct manipulation mode where the user can further explore a generated structure by moving nodes and in real-time

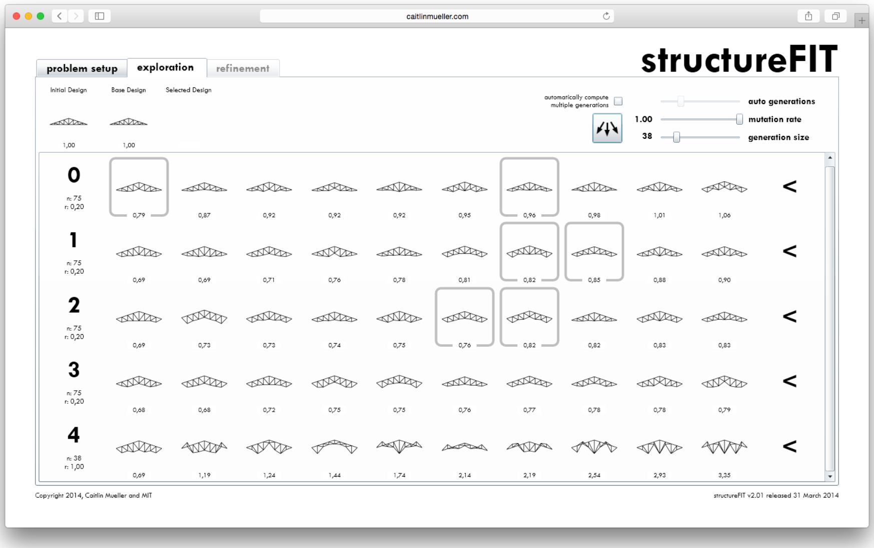

Figure 4.6: Screenshot of StructureFIT

see how a relative performance index is updated. Another version of this tool has been developed for Grasshopper [51], named Stormcloud [65].

4.3.4 Topology optimization design tools

Two other applications that were developed in academia for design exploration through the use of topology optimization are ForcePad (see Figure 4.7) [66] and TopOpt [67]. In the two applications a 2D geometry is modeled by use of conventional drawing tools, a metaphor for "drawing with stiffness". A topology optimization is then performed on the geometry and the resulting optimized shape is visualized. The applications also have an interactive mode where forces can be manipulated, and the resulting stresses updated in real-time.

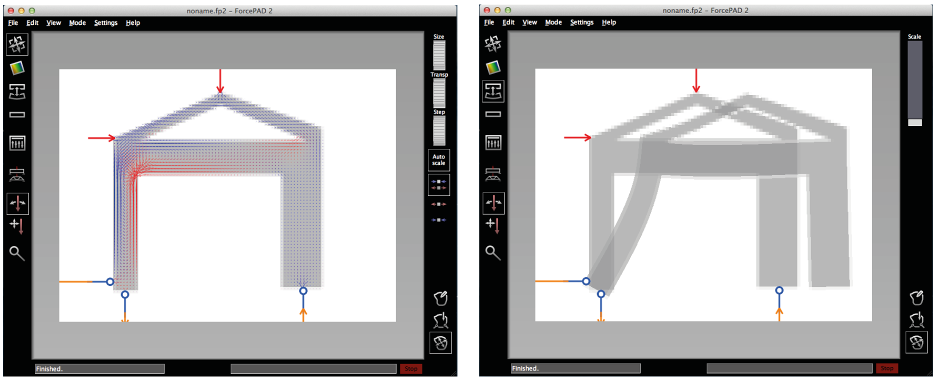

Figure 4.7: Software tool ForcePad

5 Integrating structural feedback in conceptual design tools

In the conventional workflow the architect uses geometric modelling tools and the engineer deploys structural analysis tools in a sequential step. Parametric modeling tools are an improvement to this workflow, as structural analysis plug-ins are available. This allows the user to get structural feedback earlier in the design phase, but still as a sequential step to the geometric modeling.

The present work purposes an improvement to the workflow by integrating structural feedback with geometric modeling. However, this creates new demands on conceptual design tools.

5.1 HUMAN-COMPUTER INTERACTION

The conceptual design tools should inspire and encourage the user to explore design alternatives. This puts demands on the human-computer interaction of such tools. The tools need to be interactive and allow the user to, quickly create new models, or to make changes to existing models.

Direct manipulation is a human-computer interaction style that enables the user to directly manipulate objects on the screen, and by doing so, reducing the perceptual and cognitive resources required to understand and use the user interface. In Paper 1, a conceptual design tool has been created which employs a very direct manipulation user interface for 2D. This is achieved by taking advantage of the multi-touch screen – which literally closes the gap between human and computer. In this work, the user can input a structural model by using gestures similar to those found in drawing applications for tablets, see Figure 5.1. This allows the user to quickly explore different design alternatives.

Achieving a very direct manipulation in 3D is today possible with the emergence of new 3D input controllers. This creates an opportunity to create conceptual design

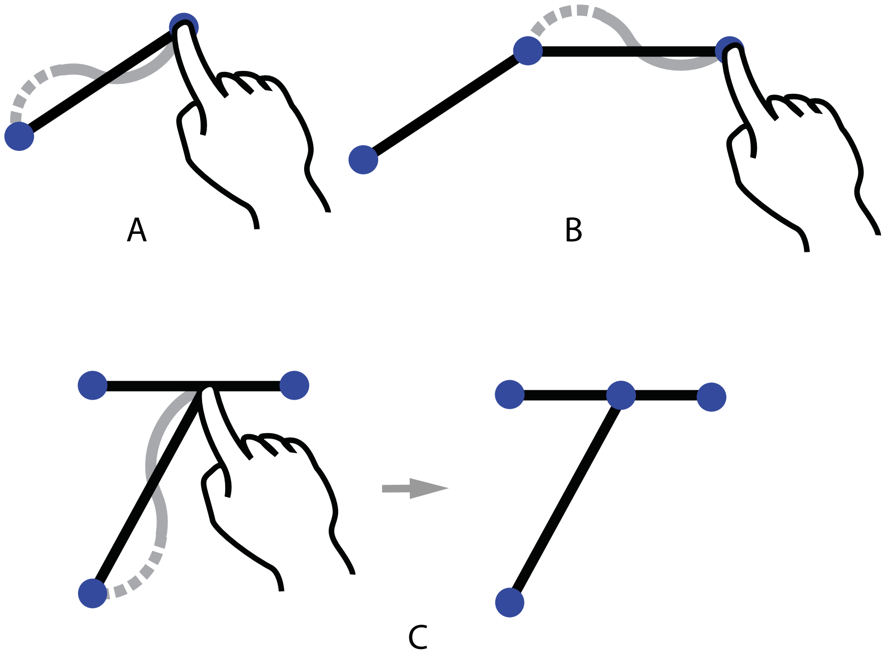

Figure 5.1: Modelling gestures in the developed application Sketch a Frame

tools with a very direct manipulation for 3D. In Paper B, this opportunity has been explored by developing a conceptual design tools which employs a very direct manipulation for 3D. This has been achieved by using a 3D input controller named the Leap Motion Controller.

In Paper A, a very direct manipulation cycle is purposed which further improves interactivity of the user interface of conceptual design application. As the user is modelling, computations are continuously performed, and when the modeled structure is stable the result is automatically visualized. This removes the need for a specific “compute step” which further integrate structural feedback into the geometric modelling. This direct manipulation cycle is also employed in the developed application in Paper B.

5.2 STRUCTURAL FEEDBACK

To integrate structural feedback into conceptual design applications structural analysis must be integrated with the geometrical modeling. The feedback should also be easy to understand and provide valuable feedback of the structural behavior and performance.

In the developed applications in Paper A and Paper B, an external force can be

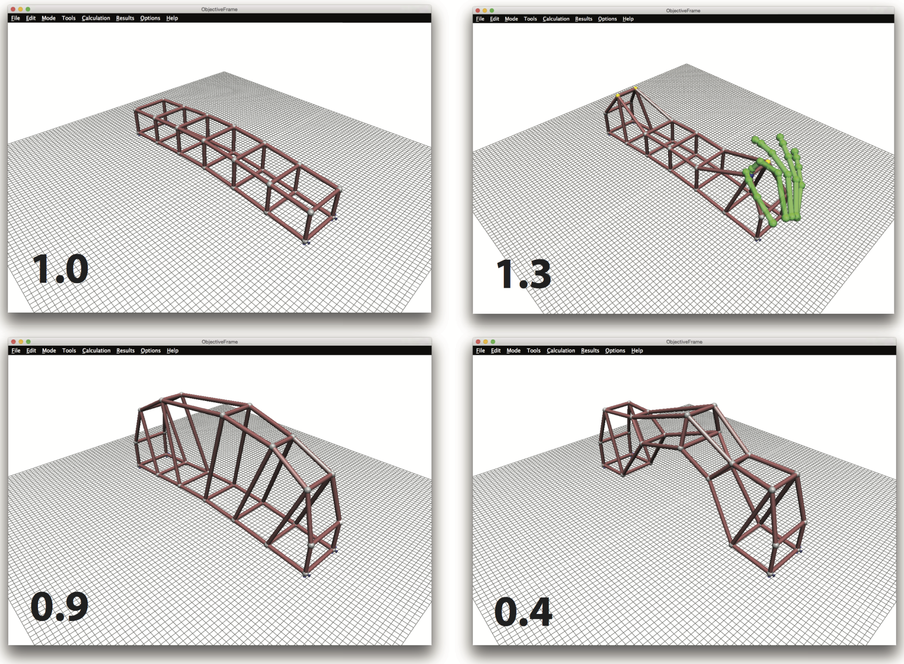

Figure 5.2: Geometric modeling with real-time performance index

applied to the modeled structure. If the model is stable – the resulting deformations can be visualized in real-time. The user can then manipulate the force using direct manipulation, and in real-time see how the structural deformation responds. In Paper A, when an external force has been applied, the resulting normal forces and the moment envelope can also be visualized in real-time. This can improve the user's understanding of, how the structure responds to external forces - how stresses follow through the different members, and the stiffness of the structure in different directions.

The structural feedback should be easy to understand for the user. In Paper B, a model can be manipulated by the previously described direct manipulation methods, simultaneously the user is presented with a performance index, which is a measure of how well performing the structure is. The performance index is the normalized strain energy of the model; thus a lower number means a better performing structure, see Figure 5.2. Presenting a single number that represents how well performing the structure is makes it easy for the user to understand how geometrical modifications affects the structural performance.

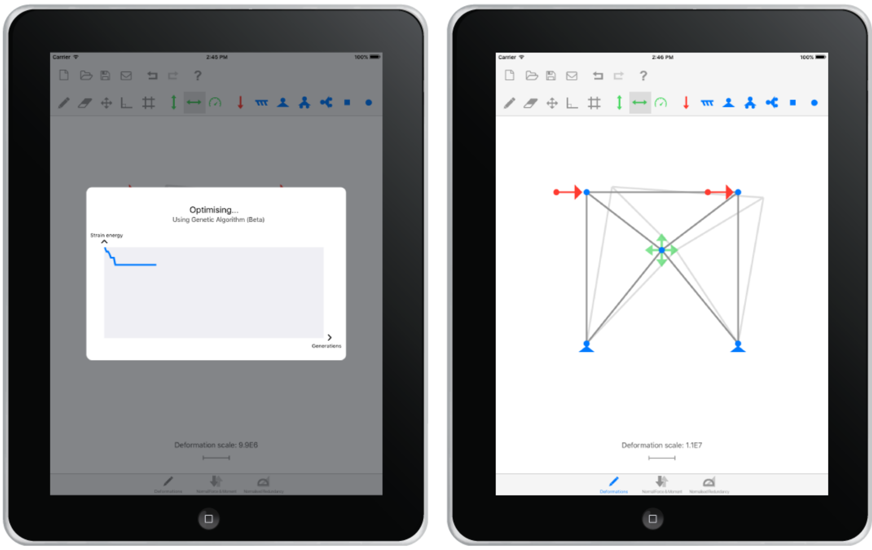

Figure 5.3: Genetic algorithm optimization in Sketch a Frame

5.3 STRUCTURAL OPTIMIZATION

Integrating structural optimization into conceptual structural design has the possibility to not only give feedback of the structural performance but also to guide the user towards geometries that are structurally well performing.

A genetic algorithm has been implemented in the application described in Paper A, which can be used for shape optimization. The user first selects which nodes and in which direction (vertical or horizontal) that the optimizer is allowed to move the nodes. Then the optimization can be executed and the strain energy is minimized. After the analysis is complete the best performing structure is visualized, see Figure 5.3.

Form finding can be used to find the static equilibrium for a structure under load. In Paper B, the dynamic relaxation method has been implemented to enable form finding in an interactive 3D environment. The user can further explore the form found structure by applying and manipulating an external force. The point load can here be used to move away from the optimal solution in order to find other interesting sub optimal solutions that might be more aesthetically attractive to the user. The point load can also, for example, represent a supporting column or a hanging installation in the structure.

5.4 VISUAL REPRESENTATIONS

After structural analysis computations have been performed the result can be visualized. For conceptual structural design tools, visualization where the user can quickly get an understanding of the results are sought.

One such example is graphostatics, which visualize forces as lengths of lines in the force diagram. This is beneficial for the users understanding, compared to using colors to represent the size of the forces, as it removes a layer of abstraction. The user can directly understand the size of the forces without the need of a for example a colorbar.

To visualize dynamic behavior animations can be used. This is used in the application developed in Paper A – if a force is applied to a non-stable model the corresponding mechanism is visualized by using an animation. This allows the user to quickly understand the model's non-stable behavior, and how the model needs to be modified in order to make it stable.

5.4.1 Example - Loadpaths

Structural behavior of 1D elements, such as bar and beam elements, are easier to understand than higher dimensional elements. Higher dimensional elements have a more complex structural behavior. For 2D structural elements the internal stresses can be computed and used to compute lines which represents how the external load flows through the structure towards the boundary conditions. Here described for the Z-direction [70]:

$$\frac{\delta \tau_{xz}}{\delta x} + \frac{\delta \tau_{yz}}{\delta y} + \frac{\delta \sigma_z}{\delta z} = 0$$

The author has explored how loadpaths can be extended into 3D by using volumetric elements. The idea for the algorithm and the result is shown in Figure 5.4. Volumetric elements are colored according to the von Mises stress and the green dots are boundary conditions. However, this method does have some drawbacks; it is unclear how to interpret the lines, sensitivity to the mesh and computational heavy. Also, only the internal stresses acting in the Z-direction are here considered.

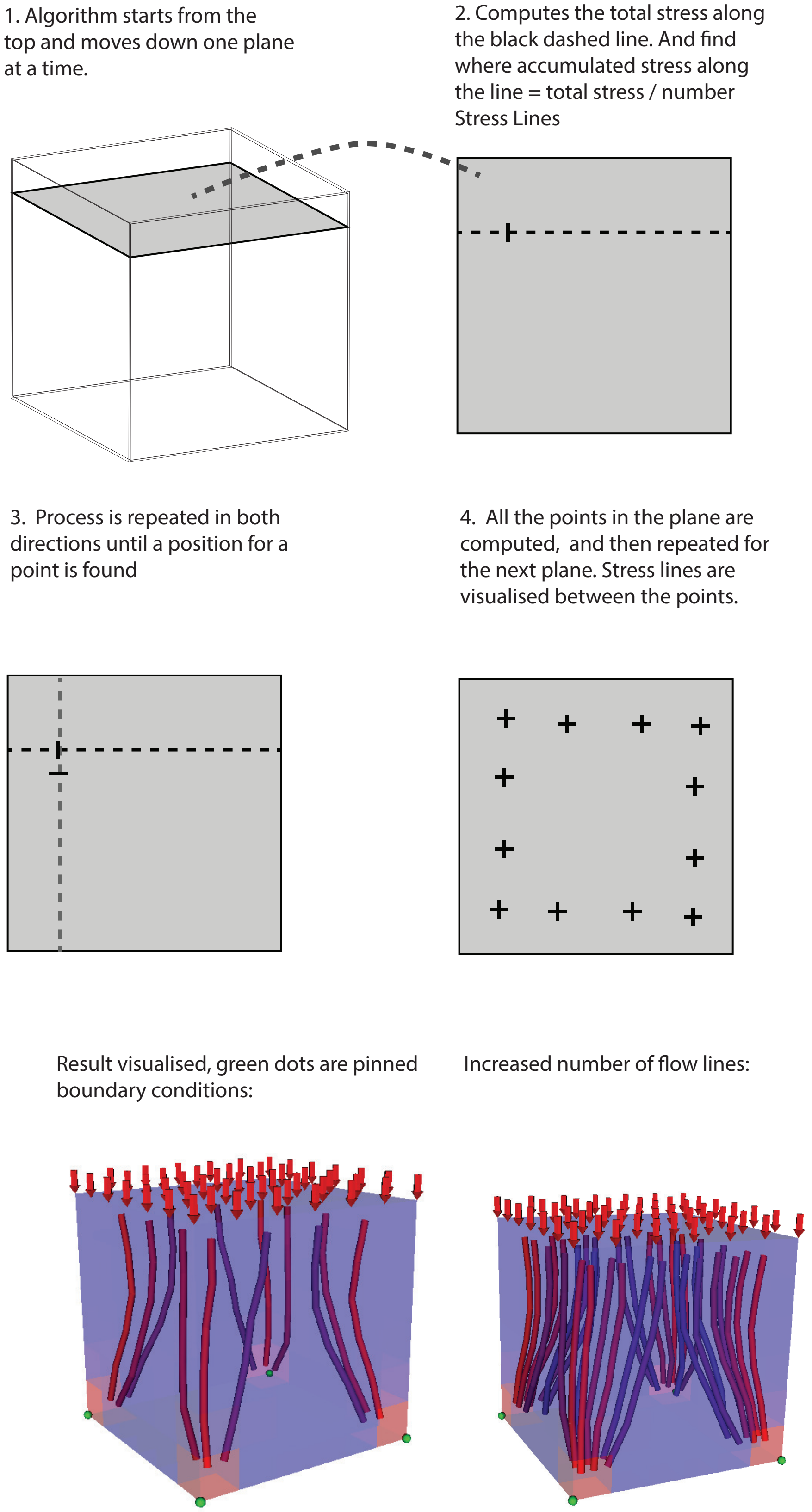

Figure 5.4: Computing loadpaths for 3D

6 Summary of appended papers

6.1 PAPER A

A tablet computer application for conceptual design
D. Åkesson, Lund University
J. Lindemann, Lund University
Accepted for publication in Engineering and Computational Mechanics, 2015

SUMMARY

A tablet computer application for conceptual design has been developed, named Sketch a Frame. The application uses a direct manipulation cycle, where the result is computed and visualized in real-time when the structural model is stable - moving away from the conventional structural analysis software step-by-step workflow. If the model is not stable and a force is applied, the first modal shape is visualized by use of animation.

The different results from the computations that are presented in the application are: normal force, moment envelope, stress and normalized redundancy. No numerical values are presented for the user from the computations; this is a design decision to encourage the user to focus on the general structural behavior and not the exact numerical results.

The application has a very direct manipulation user interface not before achieved for this type of application.

Contribution

I, as first author, have done all of the new implementations in the work. I have also written the paper. Jonas Lindemann came with the initial idea, and have supervised the work.

6.2 PAPER B

Using 3D direct manipulation for real-time structural design exploration
D. Åkesson, Lund University
C. Mueller, Massachusetts Institute of Technology
Submitted

Summary

A proof of concept conceptual design application has been developed, with an unprecedented very direct manipulation user interface for 3D. A pre-existing application named ObjectiveFrame is combined with the 3D input device named the Leap Motion controller, allowing the user to directly interact with a structural model by using hand gestures.

Three different cases were implemented:

- *Structural feedback* – The user can apply and manipulate, a force to a structure by interacting with the hands. Creating a metaphor that the user can get a feeling for how the structure feels.
- *Performance feedback* – The user can move nodes by interacting with the hands. A performance index is presented to the user giving feedback for how geometric manipulations changes the structural performance.
- *Dynamic relaxation* – The dynamic relaxation method is used together with a gravity load and a point load that can be manipulated. This creates an interactive case where the structure constantly converges to static equilibrium using an animation.

Contribution

I, as first author, have done all of the new implementations in the work. I have also written the paper. Caitlin Mueller have supervised the work and shared ideas for the development. She has also helped with how to communicate the new ideas in the paper.

7 Results & discussion

A summary of the evaluated conceptual design tools can be seen in Figure 7.1, the tools are grouped according to number of dimensions and how direct the manipulation is experienced. The two developed applications have a higher degree of direct manipulation for 2D and for 3D than any other existing software for conceptual design. This is achieved by using novel technology, the multi-touch user interface for 2D and the Leap Motion Controller for 3D.

The thesis responds to a need for new, more intuitive and natural interaction modes in computational design and analysis. Very direct manipulation improves significantly beyond existing direct manipulation paradigms prevalent in computer-aided design. New technologies like the Leap Motion controller and the multi-touch interface open up unprecedented possibilities for engaging users in the exploration and design of structures. Which can improve the user's understanding of the structural behavior of a model, cognitive engagement in the task performed, and encourage further design exploration.

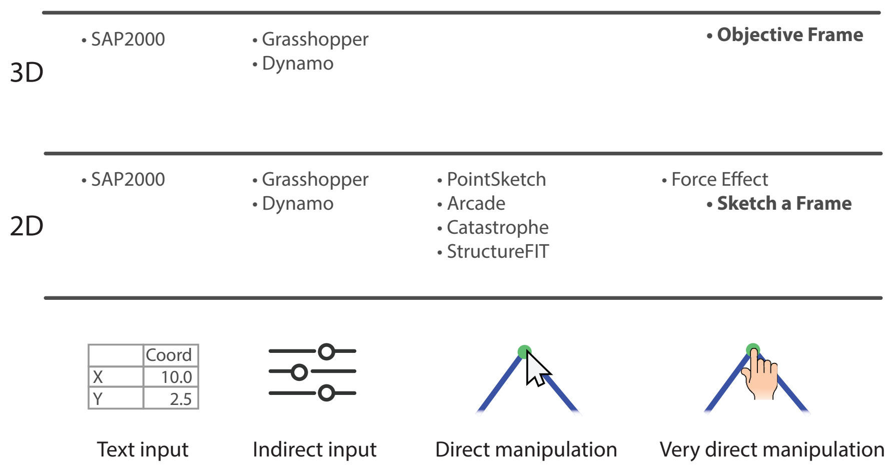

Figure 7.1: Previous and work summarized in present work in bold

7.1 SUMMARY OF INTELLECTUAL CONTRIBUTIONS

- Thesis includes critical review of existing tools and techniques for design manipulation in conceptual computer-aided design.
- Paper A proposes a new direct manipulation cycle that automatically computes and presents the result when a structure is stable.
- Paper A introduces new multi-touch interaction models for conceptual structural design on tablets.
- Paper B is the first paper to propose very direct manipulation as human-computer interaction mode for 3D structures, thanks to new 3D input device such as Leap Motion controller
- Paper B, introduces implemented design tool that allows users to interact with 3D structures through very direct manipulation.
- Paper B demonstrates potential applications of 3D input devices through three case studies.

7.2 FUTURE WORK

The Leap Motion controller's SDK supports virtual reality glasses, such as the Oculus Rift. Combining the two can create a virtual reality where the user can experience the structure in 3D, interact, and make changes to it using the hands.

This could potentially be developed in a game environment where the structure could be visualized in the intended context i.e. the building site, a game engine would enable real-time renderings of the structure in its context. The designer would then be able to make manipulations, guided with performance feedback, to the rendered structure.

Other existing design methods could be combined with this design environment, such as interactive optimization with the use of genetic algorithm. To improve computational speed, and allow fast generation of new designs, the design space can be approximated with the help of neural networks, also known as surrogate modeling. This can allow for more advanced structural models to be used for interactive optimization.

Case studies will be performed to study, and verify, the benefits of using the developed conceptual structural design tools.

References

[1] Schlaich, M. (2006), *Challenges in Education–Conceptual and Structural Design*, in: *IABSE Symposium Report*, vol. 92, 20–26, International Association for Bridge and Structural Engineering.

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Part II

Appended publications

Paper A

Engineering and Computational Mechanics

A tablet computer application for conceptual design
Åkesson and Lindemann

ice | proceedings

Proceedings of the Institution of Civil Engineers

http://dx.doi.org/10.1680/eacm.14.00020
Paper 1400020
Received 18/08/2014 Accepted 05/03/2015
Keywords: computational mechanics/design methods & aids/education & training

ice Institution of Civil Engineers publishing

A tablet computer application for conceptual design

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In the conceptual design phase, solutions are reached through an iterative, high-paced and often chaotic manner. Conventional advanced structural analysis software is often too advanced and insufficiently agile to follow this high-paced work pattern. Premature use of advanced structural analysis tools can negatively affect conceptual understanding and the quality of the conceptual design. The multi-touch interfaces of today's tablet computers give the user a strong feeling of direct manipulation of objects on the screen. This is interesting for structural mechanics applications, enabling direct manipulation of the structural model on the screen so as to have a better understanding and feeling of the structural behaviour. A tablet computer application for the conceptual design phase, which uses this type of direct manipulation interface, has been developed.

1. Introduction

> In practice a great many problems are solved by what is called judgment. The better a man understand how the stresses follow through a member or structure, the better his judgment will be. (Wolfe, 1921)

The earliest phase of the design process is referred to as the conceptual design stage. This stage is distinguished from the later design stages by more general questions and solutions (McNeill *et al.*, 1998). The conceptual design stage starts with a general description of a problem and ends, after the creation and exploration of new ideas, with a general description of a solution (McNeill *et al.*, 1998), in this case a structure. A structure is born during the conceptual design phase, and problems that arise in later design stages are often a result of careless conceptual design (Schlaich, 2006).

In the conceptual design phase, solutions are reached through an iterative, high-paced and often chaotic manner (Schlaich, 2006). Conventional advanced structural analysis software is often too advanced and insufficiently agile to follow such highly paced work patterns. It has been shown that premature use of advanced structural analysis tools can negatively affect the conceptual understanding and the quality of the conceptual design (Fröderberg and Crocetti, 2014).

The importance of the conceptual design stage is often overlooked and structural aspects are only considered in a late design stage (Schlaich, 2006). Structural engineers are in need of an improved conceptual design toolbox (Fröderberg and Crocetti, 2014), and new computer-aided tools could be a part of this toolbox.

New technology opens up new possibilities for computer-aided tools in the conceptual design phase. The iPhone, launched in 2007 (Kerris and Dowling, 2007), featured a revolutionary new input technology – the multi-touch interface. This is a touch screen that allows interaction with multiple fingers simultaneously, making it possible to interact using gestures, such as pinch to zoom or swipe to turn page.

The multi-touch interface has closed the gap between human and computer, giving the user a stronger feeling of directly manipulating objects on a screen (Sears *et al.*, 1993). This makes it interesting for conceptual structural design applications, giving the user the ability to directly manipulate the model on the screen, which could result in a better understanding and feeling of structural behaviour. These possibilities are explored in this paper. A measurement of normalised redundancy has also been implemented; for further details see Tibert and Achi (2012).

2. Previous work

The emerging field of conceptual structural design computation seeks to close the gap between visualisation tools and computational analysis tools (Mueller, 2014). Numerous applications exist for conceptual structural design. Two different key features – guidance and feedback – can be identified for design tools that encourage integrated conceptual design (Mueller, 2014).

2.1 Guidance features

Applications with guidance features suggest new geometries to the user in order to improve the structural performance of the model (Mueller, 2014). These applications make use of different optimisation techniques to compute new geometries that are presented for the user. Two interesting similar applications that make use of topology optimisation are Forcepad (Lindemann *et al.*, 2004) and Topopt (Aage *et al.*, 2013); in these two applications, a two-dimensional geometry is modelled, a topology optimisation is then performed and the resulting optimised shape is visualised.

Another optimisation technique that can be used for conceptual structural design is the genetic algorithm (Goldberg, 1989). The two applications Structurefit (Mueller, 2014) and Evolutionary design tool (Von Buelow, 2008) make use of this technique to optimise the shape of truss networks. One of the strengths of using evolutionary computing in this context is that local optima can be determined and presented to the user as structurally well-performing design alternatives.

2.2 Feedback features

This type of application responds quickly to the user's input, ideally in real-time, to allow for an interactive user experience (Mueller, 2014). Numerous applications that implement real-time numerical analysis have been developed both for practice and for research. Two of the first applications to implement this approach were Pointsketch (Olsson, 2006), which was the inspiration for the present work, and an application called Arcade (Martini, 2006). These two applications make use of the finite-element method and bar elements, which the user can interact with using a mouse and keyboard user interface.

The commercial and widespread finite-element analysis (FEA) software SAP2000 introduced, in version 12, a 'model alive' feature that gives real-time feedback for forces and deformations in truss networks (Clune *et al.*, 2012). More recently, Autodesk – a software company known for visualisation tools – launched its new application ForceEffect both as a tablet and as a web application (Autodesk, 2015). The application is a tool for engineers to visualise and analyse truss networks, and also has support for visualising rigid body motions. According to Mueller (2014), 'the advantage of this class of tools over traditional structural analysis programs is the speed with which they convey results'.

3. FEA software in the conceptual design phase

Conventional FEA software is designed for later design stages, not the conceptual design phase. As the conceptual design phase has more general questions and solutions (McNeill *et al.*, 1998), software needs to be adapted accordingly. Often, conventional software is too complicated and time consuming to use, which does not integrate well with a designer's iterative workflow (Lindemann *et al.*, 2010).

4. Sketch-a-frame – a conceptual structural design tool

Sketch-a-frame is a finite-element iPad (Apple, 2014a) application for the conceptual design phase that makes use of beam elements. The application is free to download and available in the Appstore for iPad. The user interface is designed with the intention to be fast, intuitive and easy to understand. Instead of the conventional simulation sequence (see Figure 1), a more direct manipulation cycle is used, as shown in Figure 2.

The result is visualised when the model is considered complete; that is, if boundary conditions and one or more forces have been applied. When the model is complete it is determined if any rigid body motions are possible by calculating the determinant of the stiffness matrix; if the determinant is non-zero the model is stable. If the model is not stable and rigid body motions are possible an eigenvalue analysis is performed; the first modal shape is then visualised with an animation.

Computations are performed in real-time as changes are made to the geometry (e.g. when a node is moved the result is continuously updated and visualised; see Figure 2). Real-time visualisation encourages the user to experiment with the model in an explorative manner.

The application presents no numerical values on the geometry, forces or deformations. This is a design decision to encourage the user to focus on the general structural behaviour and not on the exact numerical results. This is not a tool to dimension structural members and therefore the material properties used are not relevant.

5. Theory and implementation

The application was developed using C++ and Objective-C. Finite-element computations are performed in C++ for performance reasons, using an external library called Newmat (Davies, 2014) for matrix operations. Newmat contains classes for common matrix and vector operations. The user interface was developed using Objective-C.

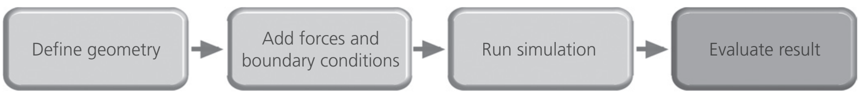

Figure 1. Conventional simulation sequence

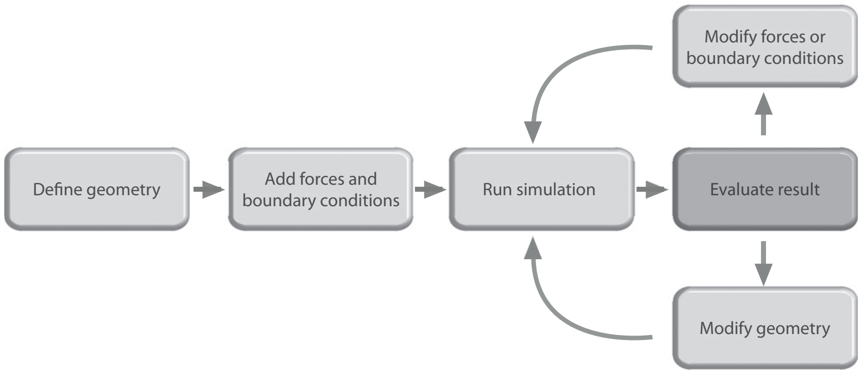

Figure 2. Direct manipulation cycle

5.1 Finite-element model

Beam elements (Bathe, 1996) are used for the computations. Every node has three degrees of freedom (DOFs) – vertical, horizontal and rotational – as shown in Figure 3.

5.2 Eigenvalue analysis

From the stiffness matrix $\mathbf{K}$ of a structure, a set of scalar stiffness values can be determined (Olsson and Thelin, 2003). Assume that a set of displacements $\boldsymbol{a}$ exists, which are proportional to a corresponding set of forces $\boldsymbol{f}$

$$\boldsymbol{f} = \lambda \boldsymbol{a}$$

This can be combined with a linear elastic finite-element formulation

$$\mathbf{K}\boldsymbol{a} = \boldsymbol{f} = \lambda \boldsymbol{a}$$

which can be rewritten as

$$(\mathbf{K} - \lambda \mathbf{I})\boldsymbol{a} = 0$$

This is a standard eigenproblem. The eigenvalues λ have dimensions of force/length, also called canonical stiffness values (Olsson, 2006). Every eigenvalue λ_i has a corresponding eigenvector $\boldsymbol{a}_i$, which describes a modal shape. Eigenvalues equal to zero means zero energy is required to form the corresponding modal shape (i.e. a rigid body motion). The eigenvectors are only defined within a scalar multiple. The eigenvector is normalised and multiplied by a positive and negative scalar, and the result is two different shapes. An animation of the rigid body motion can be achieved by interpolating between the two different shapes; this is implemented in Sketch-a-frame.

Figure 3. Beam element with six DOFs

5.3 Static redundancy factor

In Sketch-a-frame, normalised static redundancy factors are presented as a way to assess the redundancy of individual elements in the structure (Tibert and Achi, 2012). Only topology and geometry are studied in the analysis. Using the equilibrium matrix $\mathbf{H}$, described in detail by Pellegrino and Calladine (1986), and the diagonal elements stiffness matrix $\boldsymbol{\Psi}$ yields (Tibert and Achi, 2012)

$$\boldsymbol{\Lambda} = \mathbf{I} - \mathbf{H}^{\mathrm{T}}(\mathbf{H}\Psi\mathbf{H}^{\mathrm{T}})^{-1}\mathbf{H}\Psi$$

The trace of the scaling matrix $\boldsymbol{\Lambda}$ is equal to the degree of static indeterminacy s

$$\mathrm{tr}(\boldsymbol{\Lambda}) = s$$

Thus, every diagonal element Λ_{ii} can be interpreted as element i's contribution to the structure's static indeterminacy, and is hence denoted the static redundancy factor. In Sketch-a-frame, the result is normalised and visualised using a colour scale (see Figure 4). Elements coloured blue cannot be removed without rendering the structure unstable, while elements coloured red are highly redundant. If there are any changes in the geometry (e.g. a bar is added or removed), the updated result is computed and visualised automatically.

In Example A of Figure 5, the vertical bar is 0% redundant as it is the only bar that provides vertical stiffness to the structure.

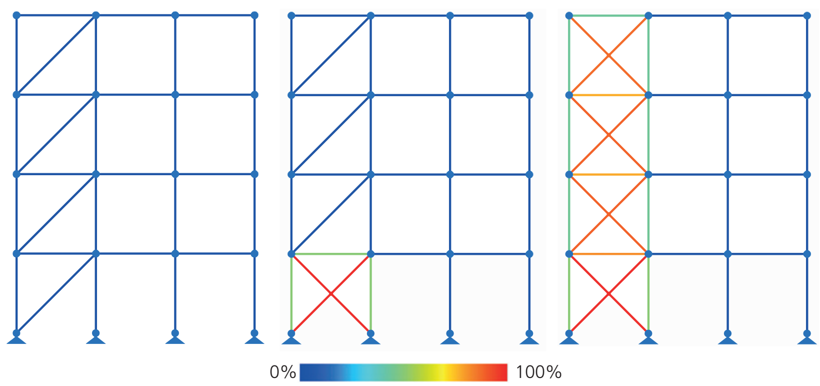

Figure 4. Normalised degree of redundancy

In Example B, the element coloured red is the most redundant element, but any element could be removed without rendering the structure unstable.

6. User interface

To make it easy for the tablet user to understand how different applications work it is important that there is consistency between them. Apple has guidelines for developers (Apple, 2014b). How an application works should not be based on the capabilities of the device, but on the way people think and work. The application should also be optimised for the device that it is running on. Aesthetic integrity is also of importance; it is not only about creating something beautiful, it is also how the design integrates with the functionality of the application.

Users enjoy direct manipulation on the screen – it keeps them engaged and gives a feeling of control (Apple, 2014b). Direct manipulation is a user interface style with continuous representation of objects of interest with rapid, reversible and incremental feedback (Shneiderman, 1982). Users can directly manipulate objects on the screen using real-world metaphors.

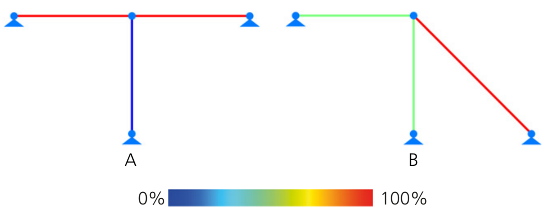

Figure 5. Normalised degree of redundancy, further examples

This user interface style creates intuitive user interfaces that work very well with the multi-touch screen (Sears *et al.*, 1993).

6.1 General layout of application

During the development process of the user interface, the quick and dirty evaluation paradigm (Rogers *et al.*, 2011) was used to quickly get feedback from users. In this paradigm, users are observed as they interact with the application with minimal control from the evaluators. Later in the development process, the usability testing evaluation paradigm (Rogers *et al.*, 2011) was used to review the performance of the interface and find further improvements. In the evaluation paradigm, users were given a task to perform as they were recorded using a camera, to be used for later assessments.

The goal of the user interface development was to create a simple to use and intuitive user interface. Feedback from the users guided the development to a user interface with three different pre-set visualisation modes (see Figure 6) available in a tab bar. The different modelling tools are always visible and accessible for the user in a toolbar. The three different visualisation modes are

- deformations
- normal force and moment
- normalised redundancy.

Figure 6. The three different visualisation modes

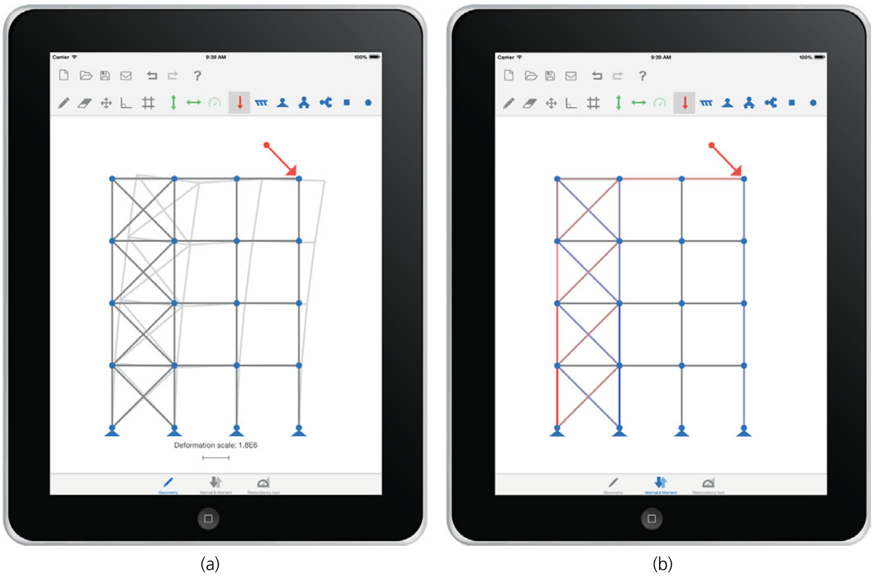

Figure 7. (a) Deformations visualised; (b) normal force visualised

In the deformations mode, the deformed shape is visualised (see Figure 7(a)). In the normal force and moment mode, the normal force is visualised by colouring the elements red (for tension) and blue (for compression), as shown in Figure 7(b). If moment constraints exist, a moment envelope is visualised.

The application also has support for sharing the result. A pre-composed e-mail can be sent containing all the results in image format and a model file, which can be re-opened in the application.

6.2 Geometric modelling

As shown in Figure 8, the modelling tools available to the user in the toolbar are

- pen – swipe to create elements and nodes
- eraser – swipe or tap to remove elements and nodes
- move – moves nodes; result is visualised in real-time during the movement
- undo and redo – changes can be undone and redone
- grid – a grid is shown that the tools snap against
- ortho – elements created are vertical or horizontal.

While using the pen tool and a swipe gesture is initiated, a node is created; when the gesture is released, an end node and an element between the nodes is created, as shown in Figure 9(a). When a swipe gesture is active, an element is visualised to the current position; if the current position is close to a node or a

Figure 8. Modelling tools

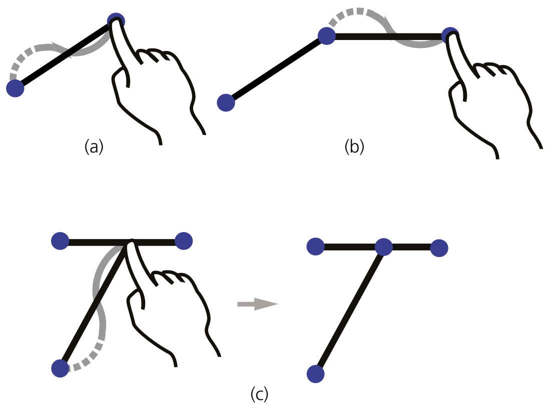

Figure 9. (a) Element created on release; (b) element connected from existing node; (c) new element connected to existing on release

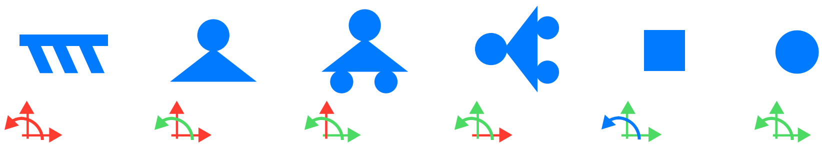

Figure 10. Boundary conditions: red arrows represent constrained DOFs, green arrows represent unconstrained DOFs and blue arrow can transfer bending moment between elements

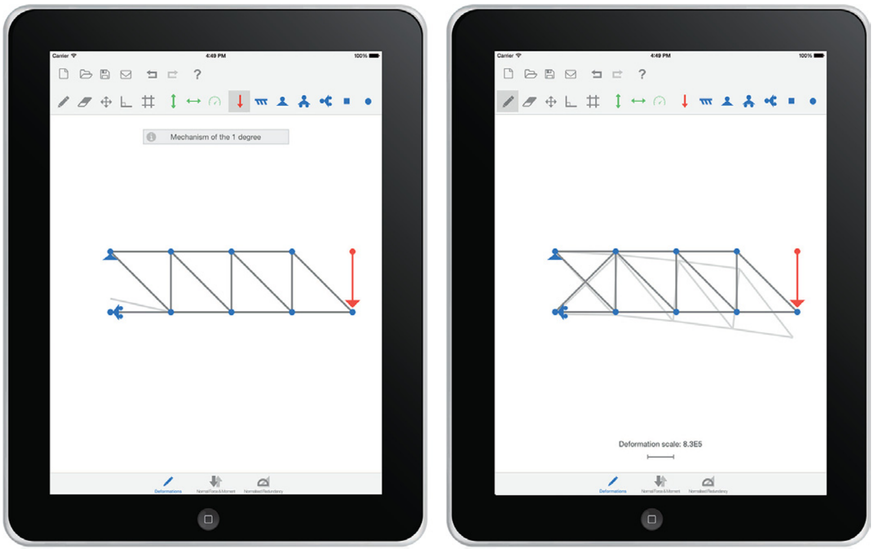

Figure 11. Assignment solved

line, the visualised element snaps to it. This also fits well in the direct manipulation of objects with continuous representation of objects of interest. This allows for a line or node to be the start or the end point of a new element (see Figures 9(b) and 9(c)).

6.3 Boundary conditions and forces

As beam elements are used, every node has three DOFs (i.e. vertical and horizontal translation and rotation), which can be constrained in different combinations. For simplicity, six of the most common combinations are implemented with symbols familiar to engineers (see Figure 10).

A force tool is also available. Tapping or swiping on nodes using this tool adds forces to the selected node. Forces can also be adjusted using the force tool and as the force is adjusted the result is visualised in real-time.

6.4 Scale

The difference in deformations between two models can be up to a factor of 10^9 times, depending on the stiffness of the model. To be able to visualise the deformation independently of the stiffness of the models, it needs to be scaled. However, constant rescaling removes some of the important feeling of directly manipulating the model. Rescaling when a swipe gesture is released was the best solution found; this retains the feeling of direct manipulation and allows the deformations to be visualised properly.

The current scale is presented to the user at the bottom of the screen together with a scale bar. The scale bar is always the same length as the largest deformation, and rescales when a swipe gesture is released. The same concept is used for visualising the moment envelope.

7. Application usage examples

7.1 Development of a roof truss structure in glulam

The application was used by two civil engineering students in their master thesis work to improve the market competiveness of glulam by developing a standardised concept for roof trusses for large open-space structures (Hedlund and Brorson, 2013). The following work process was used to find the most efficient truss designs.

- Inspiration and brainstorming – a large number of constructions was studied and evaluated. Inspiration was found from existing structures and literature, with the most successful constructions moving on to the next stage.
- Sketching – constructions were refined and improved.
- Rough design – cross-sectional forces were calculated using the software SAP2000 (CSI, 2015).
- Cost estimate based on cross-section and number of nodes.
- Selection based on comparison of stiffness, cost, number of nodes and installation.
- Final design, optimisation and cost estimation – roof trusses from the selection were further refined and a new cost estimation performed before the final design was chosen.

Sketch-a-frame was used in the first two stages in which the students brainstormed and explored different designs. The students preferred using the application over more advanced software in this conceptual design phase as a result of the speed of the interaction. The students also reported an increased initial understanding of the structural behaviour of the models.

7.2 Solving a course assignment

Some civil engineering students were given an assignment to solve. The task was to analyse a structure and determine if it was stable and, if not, give examples of improvements to make it stable. Most students solved the assignment by using Matlab and calculating the determinant of the stiffness matrix, but one of the students used Sketch-a-frame instead; the structure was quickly modelled and the result was immediately presented (see Figure 11). With animation of the rigid body motion, this student understood how the structure could be improved to make it stable and could quickly try different solutions.

8. Conclusions

The strength of tools with feedback features lies in the speed of the interaction and the fact that a freer exploration of structural forms is allowed. Sketch-a-frame further improves on the strengths of feedback feature tools as the speed of the interaction is improved with the multi-touch interface.

The multi-touch interface also gives a stronger feeling of directly manipulating the model on the screen, which encourages exploration and gives the user a feeling of control. With a higher speed of interaction, structural forms can be explored more freely compared with earlier mouse and keyboard feedback tools. However, some precision is lost with the multi-touch interface that can be a disadvantage for the geometric modelling of details. Another advantage of a tablet application is that it can easily be brought to meetings and used as a discussion tool, which can create a collaborative environment between participants.

The process of conceptual and structural design can be described by four steps – conceiving, modelling, dimensioning and detailing (Schlaich, 2006). In engineering, however, there is a lack of tools that support the first steps of conceiving and modelling. Sketch-a-frame provides such a tool. The development of the glulam roof structure is a good example of how Sketch-a-frame can be used to improve the conceptual and structural design process.

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Paper B

Using 3D direct manipulation for real-time structural design exploration

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Abstract

The impact of decisions on the design process is initially high and declines as the design matures. However, few computational tools are available for the early design phase; thus, an opportunity exists to create such tools. New technology opens up new possibilities to create new and novel computational tools. In this work, an existing application is adapted for a new three-dimensional (3D) input device called the Leap Motion Controller. The controller allows the user to interact with 3D objects on a screen using his/her fingers and hands. The result of this work is a conceptual design application that enables very direct manipulation of 3D objects on the screen to a level that has not been achieved before for this type of application in 3D. An improved human-computer interaction can potentially improve the user's understanding of the structural behavior of a model, cognitive engagement in the design task, and encourage further design exploration. Three different cases are implemented to enable the user to explore different design options with emphasis on geometrical form, as this has the greatest potential to improve structural performance. These case studies demonstrate a new potential for building engineering intuition and improving design space exploration through very direct manipulation in 3D.

Keywords

Interactive structural analysis; Interactive structural form finding; 3D input device; Dynamic relaxation; Conceptual structural design

1 Introduction

The object of this paper is to demonstrate how an interactive three-dimensional (3D) environment can improve conceptual structural design. The goal is to improve the user's understanding of the structural behavior of a model and illustrate how geometrical modifications can change its structural performance.

1.1 Conceptual design tools

The earliest phase of the design process is referred to as the conceptual design phase. Decisions made in this phase have the highest impact of all the decisions made throughout the design process [1]; the impact of decisions then declines as the design matures. The importance of the conceptual design phase is often overlooked and structural aspects are often only considered at a late design stage [2]. A factor contributing to this situation is that very few computational tools are available for conceptual design. The challenge of developing such computational tools is the fuzzy nature of the problem: the knowledge and constraints of the problem are imprecise and incomplete [3]. Conventional advanced structural analysis software requires precise knowledge of the problem and is not agile enough to follow a designer's iterative workflow. It has been shown that premature use of such software can negatively affect the quality of the conceptual design [4]. Conventional structural analysis software has been developed for use in the late design stage, when the major design decisions have already been made, as a tool for the engineer to verify the form.

Many different geometric modeling tools are available for architects today. These geometric modeling tools have, since their introduction in the 1980s, grown increasingly sophisticated, and have, together with the widespread perception of the benefits of technological innovation, created a more intimate relationship between technology and design. This relationship has resulted in parametric design and scripting methods that can generate complex shapes and forms [5]. The distinct separation in design that means that architects use geometric modeling tools and engineers use analysis tools further reinforces the architects role as form-giver and the engineer as form-verifier [6]. To move away from this separation, the term "designer" is used in this paper to represent either an engineer or architect.

The type of design tool that is used to generate and represent ideas also affects the quality and quantity of early prototypes. It was shown in [7] that physical prototyping generates a higher quantity of prototypes within a limited amount of time. The developed prototypes were also perceived as more novel compared to the prototypes that where developed using computer aided design (CAD) or conventional sketches. However, the prototypes that were perceived as more novel tended to fare poorly with respect to all other measureable qualities [7]. As conceptual design is important and few conceptual design tools are available, an opportunity exists to improve the design process by developing such tools.

With new technology such as novel input devices and increased computational power comes new possibilities. The present work makes use of these possibilities to create a new way to interact with and create digital prototypes. The prototypes in this work are structural models. As a computational model is used, its measureable performance can be computed and presented in real-time to the user to potentially improve the quality of the structural models. The measureable performance and guidance in this work emphasizes the geometrical form of the structure, as this has the greatest potential to improve the structural performance. The result of the present work is a computational tool for conceptual structural design with a novel human-computer interaction interface.

1.2 Human-computer interaction

Direct manipulation is a style of human-computer interaction that has a continuous representation of the objects of interest with rapid, reversible, and incremental feedback [8]. Users can directly manipulate objects on the screen using real-world metaphors, which makes the users more engaged with their task and encouraged to explore further [9]. This is achieved by reducing the perceptual and cognitive resources required to understand and use the user interface [10].

The introduction of different input devices such as the mouse and joystick significantly improved the human-computer interaction of user interfaces, which adapted accordingly [10]. Later, when the touch screen was introduced, it had the advantage over these previous devices of a very direct method of inputting information [10]. It closed the gap between the human and computer, and the user could literally touch objects on the screen to manipulate them.

There is a wide repertoire of interaction techniques to create direct manipulation user interfaces for 3D applications using 2D input devices such as the mouse [11]. However, because these types of input devices have one degree of freedom less than the 3D user interface, there will always be a need for gestures or similar methods.

Computer games have seen an increase in the number of novel input devices along with new styles of games to address some of the limitations of conventional systems [12], e.g., the Wii Remote [13], Microsoft's Kinect for Xbox [14], and PlayStation Move [15]. These novel input devices move away from the conventional human-computer interaction to invoke an intuitive interaction that supports the natural human method of working. Games have for a long time been perceived as fun and engaging, and it has been investigated in many different disciplines whether gaming methods can improve human-computer interaction in order to create more effective, immersive, and engaging learning or training [12]. In computer aided design tools, the user experience has been compromised by the engineering design system's step-by-step evolution. The present work moves away from the step-by-step user interface to create an interactive, gaming-like experience using a novel 3D input device.

Although beyond the scope of this paper, the interest in and development of virtual reality glasses such as the Oculus Rift [16] and PlayStation's Project Morpheus [17] have recently increased. These types of virtual reality glasses have primarily been developed for games, but other fields have also shown interest, e.g., in [18], virtual reality is used to help students understand complex structural behavior.

2 Related work

Multiple software tools for conceptual structural design that deploy truss models have previously been developed. The first two such tools, PointSketch [19] and Arcade [20], were developed in parallel and released in 2006. In both software tools, the user can create a computational model using mouse and keyboard input. Forces can then be applied to the model and the results from the computations are visualized. The two software tools were both developed in academia, but industry has shown interest in the concept.

The commercial finite element software SAP2000 launched a "model alive" feature in 2012 that enables real-time feedback for deformations and forces [21]. The software was developed for use with truss-structures. However, geometrical modifications are made through text input. Autodesk launched a new application in 2011 named ForceEffect [22], which is available both as a tablet and web application. The application was developed for designers to analyze and visualize two-dimensional truss structures. The tablet application utilizes a direct manipulation user interface style, where the user can make changes to the model by directly touching the objects. A similar application that further developed the direct manipulation of the interaction is a tablet application named Sketch-a-Frame [23]. This application updates the visualizations of the computational result in real-time as the user makes changes to the geometry, creating a very direct manipulation. Another conceptual design tool that can generate structures through interactive optimization is called StructureFIT [24,25]. This software tool also has a direct manipulation mode, where the user can further explore a generated structure by moving nodes in real-time see how a relative performance index is updated.

Recently, an interactive physics engine was developed to create a user experience inspired by games for design and education [26]. The developed physics engine has been used to create an interactive game called Catastrophe, which aims to teach users which elements are critical to system stability through play.

A popular design tool in practice is the parametric modeler Grasshopper [27], which allows the user to manipulate parametric models through the use of sliders. This can be combined with Karamba [28], which is a structural analysis tool that can also give real-time feedback as to how the structural performance changes when the input parameters are altered. A tool that implements similar functions is Autodesk's Dynamo [29].

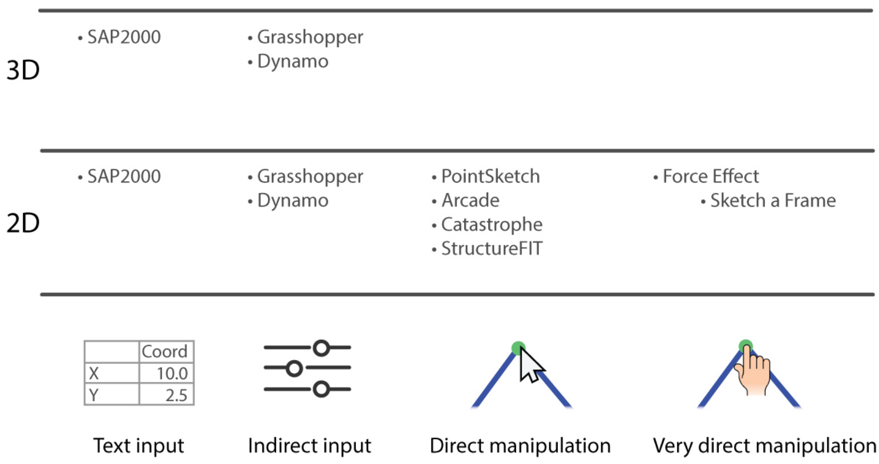

Figure 1: Summary of previous work

A summary of the evaluated conceptual design tools can be seen in Figure 1. The tools are grouped according to number of dimensions and how directly the manipulation can be experienced. Prior to the work presented here, no conceptual structural design tool has before been able to achieve very direct manipulation for 3D. A very direct manipulation user interface has so far only been achieved for 2D conceptual structural design tools. This is because of limitations of the traditional mouse and keyboard human-computer interaction with which the 3D applications were developed.

3 Methodology

The Leap Motion Controller [30] is a novel 3D input device. It can, with the use of infrared cameras, create a virtual model of a user's hands that are in the field of vision of the controller, as shown in Figure 2. This makes it possible to allow users to very directly manipulate representations of objects in 3D—which has the potential to improve the human-computer interaction of structural conceptual design applications. Improved interaction in such applications could potentially improve the user's understanding of the structural behavior of a model, cognitive engagement in the design task, and encourage further design exploration. The present work shows an implementation with a very direct manipulation for 3D that has not been achieved before for conceptual structural design tools.

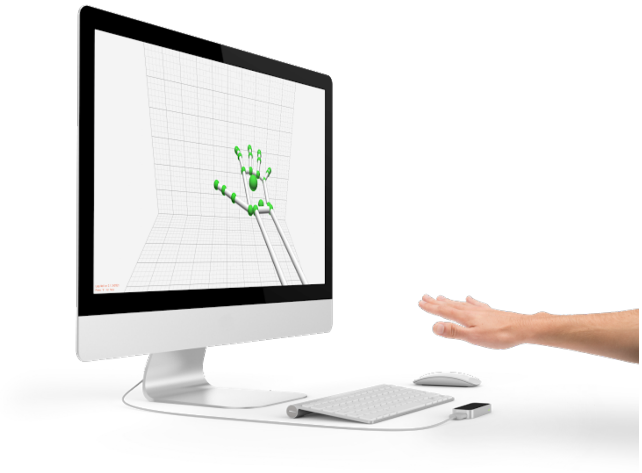

Figure 2: Leap Motion Controller in use

3.1 Leap Motion Controller

A new 3D input device for computers was launched in July 2013 called the Leap Motion Controller [30]. By connecting the controller to a computer and placing it in front of the user, it can track the movement of fingers, hands, and tools with sub millimeter precision without any visible latency [30]. A software development kit (SDK) is available and supports most common programming languages [31], which can be used to implement support for the controller in existing applications.

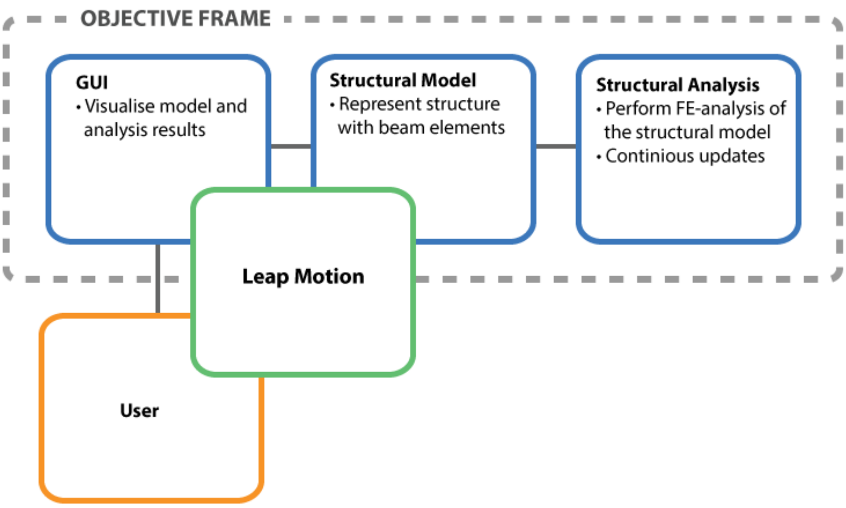

Figure 3: Conceptual diagram of how the Leap Motion Controller integrates into the existing conceptual design application ObjectiveFrame.

The SDK interprets the data from the controller's cameras and creates computational models of any hands or tools (e.g., a pen) that are in the field of vision of the controller. Using the SDK to integrate it with an application, the computational model can be accessed through the application programming interface (API), which has functions to return the positions and direction-vectors of hands, fingers, and tools in 3D. This can be used to build and visualize a virtual model of a hand or tool that can directly interact with the 3D objects on the screen. The SDK also has built-in support for gestures that can be used to call actions. This creates the potential to create very direct user interfaces for 3D, similar to the possibilities that the multi-touch user interface created for 2D.

However, new input devices require that software adapt accordingly in order to be successful [10]; thus, new 3D input devices are heavily dependent on software developers that can create new novel user interfaces.

3.2 Detailed implementation

The work in this paper builds on an existing application that was developed for conceptual structural design named ObjectiveFrame [32]. The application was developed in the C++ programming language and uses the FLTK toolkit [33] to create the graphical user interface (GUI) and the Newmat matrix library [34] to perform matrix operations.

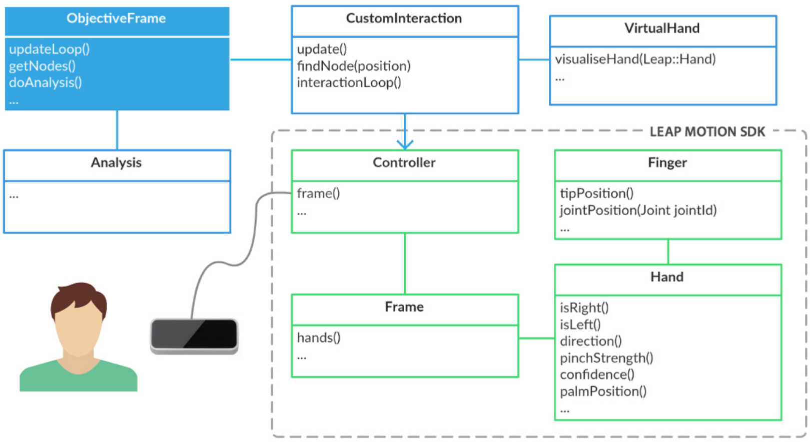

Figure 4: Diagram of how the Leap Motion SDK is integrated with the existing application.

When an instance of the class *Controller* is instantiated, the Leap Motion SDK creates a computational model of the objects in its vision field. The ObjectiveFrame application has an update cycle in which the objects of representation are continuously updated. The class *Controller* is queried at each update to obtain an updated *Frame* that contains information regarding the computational models.

Three different cases have been implemented in the existing application to demonstrate how the Leap Motion Controller can be used in the conceptual design phase.

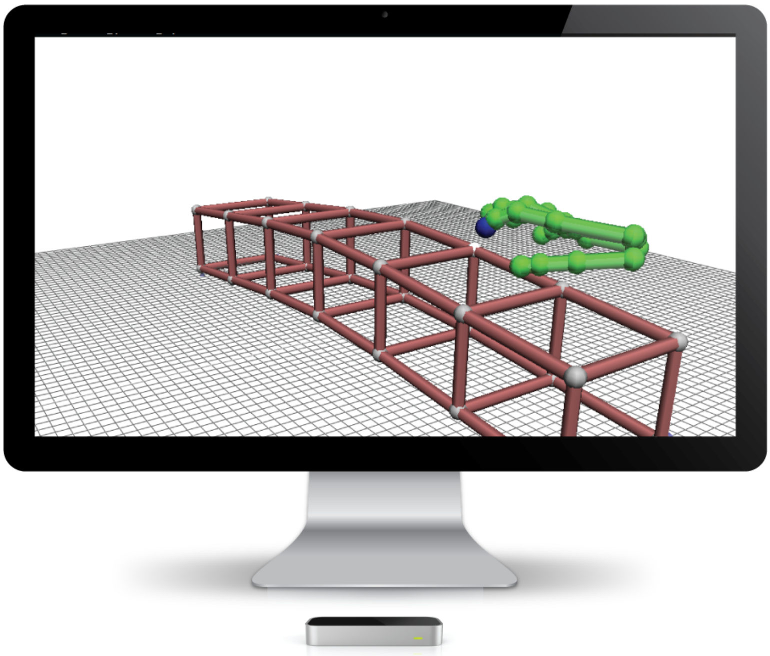

Figure 5: System setup with screenshot from the developed application.

3.3 Direct manipulation interaction model

The data from the Leap Motion SDK is used in the developed application to visualize a virtual model of the user's right hand. The tip of the index finger on the virtual hand is colored blue, as shown in Figure 6—this fingertip is used to select nodes in the 3D space. When the index fingertip position is within a set distance of a node, the node is highlighted. The user can then perform a pinch gesture (see Figure 6) to interact with the highlighted node.

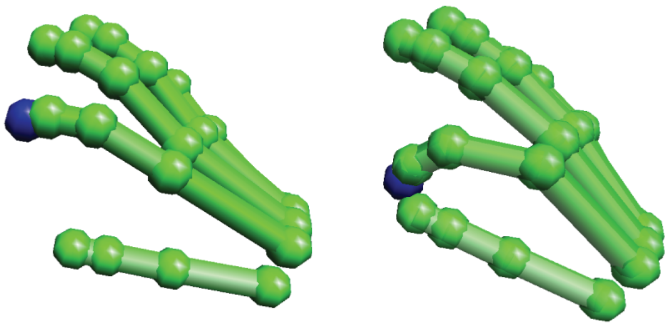

Figure 6: Pinch gesture visualized using the virtual hand model.

The right hand is used to interact with the structure while the left hand simultaneously controls the point of view, i.e., the location and angle at which the model is observed. Moving the palm closer or further away from the controller zooms out or in, respectively. This is a direct manipulation metaphor for pushing the model away. The palm position can also be used to rotate the point of view around the model by moving the palm sideways. The angle of the hand is used to control the angle at which the model is observed.

The position of the virtual hand is relative to the point of the view. Thus, when the user rotates the view, the virtual hand is rotated accordingly around the center of the view. This is in line with the metaphor in which the user reaches into the monitor to interact with the structural model. The Leap Motion SDK also has a confidence parameter. This parameter is lowered if the view is obstructed, e.g., if the left hand obstructs the view of the right hand. This is visualized using the opacity of the right hand to indicate the user that the view is obstructed.

4 Structural analysis for conceptual design

The *Analysis* block in Figure 4 shows the numerical analysis methods that have been implemented in the application to enable structural performance feedback and guidance in the application. In conceptual structural design, a simple mathematical model such as a truss or frame is advantageous for representing a structure [35]. The objective is a general understanding of the structural behavior and numerical precision is of less importance. In later design stages, the simple mathematical model can be substituted with a more advanced mathematical model for improved accuracy.

4.1 Structural analysis

To enable the application to visualize deformations and normalized structural performance, finite element analysis was implemented in the application. The application uses 3D beam finite elements that can be used to create frames or trusses to represent structures. Every beam element has two nodes—each has six degrees of freedom: three rotational and three translational ones [36]. The structural response is computed using

$$\boldsymbol{K}u = f$$

where K is the global stiffness matrix, u the displacement vector, and f the force vector. The compliance of the structure is the work (or strain energy) performed by the truss, and is the sum of the forces multiplied by the displacements:

$$W = \frac{1}{2} f^T u$$

This can be rewritten as

$$W = \frac{1}{2} u^T \boldsymbol{K} u$$

Ideally, the strain energy is a small number that corresponds to an efficient structure. To convey how geometrical modifications change the structural performance—the strain energy of the modified geometry is normalized in the developed application with the initial strain energy. The result is the normalized strain energy, a measure of how well the structure is performing.

4.2 Form finding

The process of designing form-found shapes is called form finding. Either physical models or numerical simulations can be used in this process, where the aim is to find the form for a structure under a load such that static equilibrium is satisfied. The static equilibrium corresponds to a structure that can support the applied load using only compression, and thus is a very efficient structure. For physical models, a hanging chain or cloth can be used the find the static equilibrium.

A number of different numerical methods exist to computationally find the form where static equilibrium is satisfied. The numerical method used in this work is dynamic relaxation, which is a method to solve a set of non-linear equations invented by Alistair Day in 1965 [37]. The method computes the movement of a structure over time to find equilibrium between the internal and external forces.

At each time step Δt, the internal forces for all elements are computed from nodal displacements u. The residual R can be computed using

$$R = f_{ext.} - f_{int.}$$

Using Newton's second law, the acceleration (derivative of the velocity with respect to time) can be computed as follows (at node i, in the x-direction, at time t)

$$R_{ix}^t = M_i \dot{v}_{ix}^t$$

where M_i is a lumped, fictitious mass at node i. To enforce boundary conditions, the residual is set to zero for the corresponding degrees of freedom. With a known time step, the velocity of node i in the x-direction can be computed using the finite difference method

$$v_{ix}^{t+\Delta t} = v_{ix}^{t-\Delta t/2} + \frac{\Delta t}{M_i} R_{ix}^{t}$$

With the velocity known, the updated geometry can now be updated using

$$x_i^{t+\Delta t} = x_i^t + \Delta t \cdot v_{ix}^{t-\Delta t/2}$$

After the geometry is updated, an iteration is complete and the computations start over, by again computing the residual. The geometry is modified at each iteration until equilibrium between the external and internal forces has been reached. Different types of damping such as kinetic or viscous damping can be used to get the solution to converge. In the present work, the velocities are set to zero in even intervals to obtain the desired dynamic behavior.

5 Case studies

The material parameters are not important in the following conceptual design case studies; however, they have a minor impact of the results and are therefore presented in Table 1.

Young's modulus	$2{,}1 \cdot 10^{9}$
Area	$3{,}5 \cdot 10^{-3}$
Second moment of inertia	$5{,}3 \cdot 10^{-6}$

Table 1: Material properties (representing a steel tube) used in this study

5.1 Case I: Structural response

In this case study, a point load can be applied to a structure, and the resulting deformations are then visualized in real-time. When a pinch gesture is performed on a node, a point load is applied. Then, as the user moves the pinched fingers away from the node, the applied force changes direction and magnitude accordingly. Thus, the further the user moves the hand from the start position, the larger the magnitude of the applied force. The structural deformations are continuously computed and visualized for the user. As the pinch gesture is released, the applied force is removed and the structure is visualized in its undeformed shape.

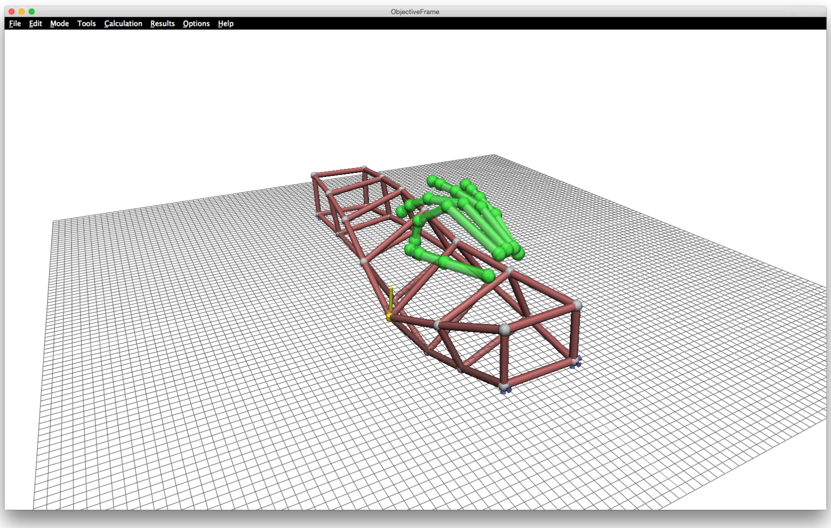

Figure 7: Structural response visualized in real-time

The scaling of the structural response is automatic and relative to the stiffness in the node where the force is applied. The applied force for node I in the x-direction is computed as follows:

$$f_{ix} = P_{currentx} - P_{startx}$$

where P_{startx} is the location of the index finger when the pinch gesture is performed and $P_{currentx}$ is the current position of the index finger.

5.2 Case II: Performance feedback

In this case, the user can move the nodes of a structural model using the pinch gesture. The strain energy of the structural model is continuously computed, normalized, and visualized on the screen for the user. The strain energy is normalized with the initial strain energy, thus the normalized strain energy is initially 1.0, where a lower value corresponds to a better performing structure.

An example of the design exploration process is shown in Figure 8; in this example, symmetry along the depth and width of the model is enforced. Thus, when a node is moved, three other nodes move to enforce symmetry. Enforcing symmetry makes the modeling process faster and different designs can easily be evaluated.

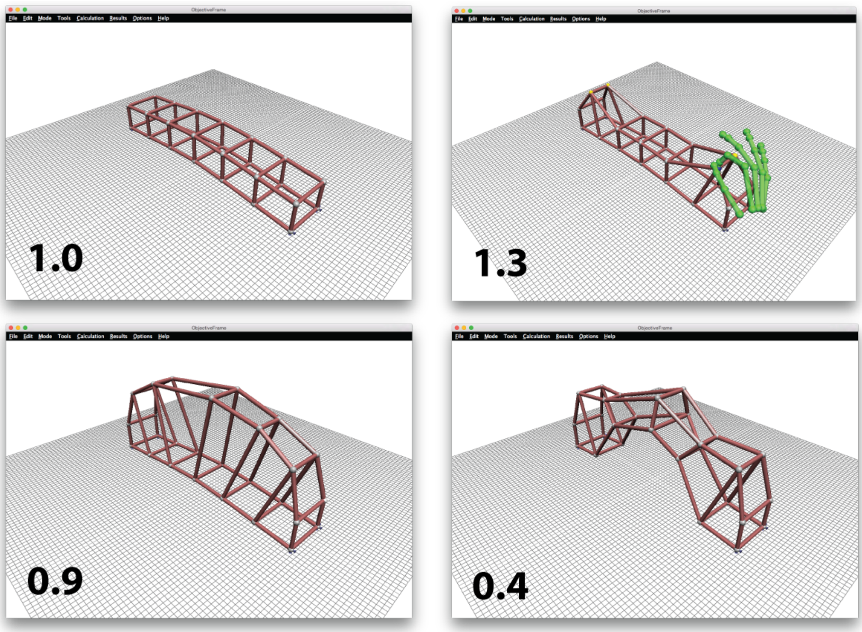

Figure 8: Design process with normalized strain energy

5.3 Case III: Dynamic relaxation

A dynamic relaxation method has also been implemented in the application. In this case, the geometry is computed and updated once every time the application refreshes. This results in an interactive application where the user can observe how the geometry is updated and modified until static equilibrium is reached.

In the following examples, a negative gravity load has been applied to the nodes. The user can then, by using the same interaction as described in Case I, apply a point load to any node. The benefit of using dynamic relaxation is that the geometry will start to converge towards the new static equilibrium even if the static equilibrium was not found for the parent load. This improves the interactivity of the application by following the direct manipulation guideline of continuously updating the object of interest. In Figure 9, an example is shown that corresponds to the physical prototype of a hanging chain.

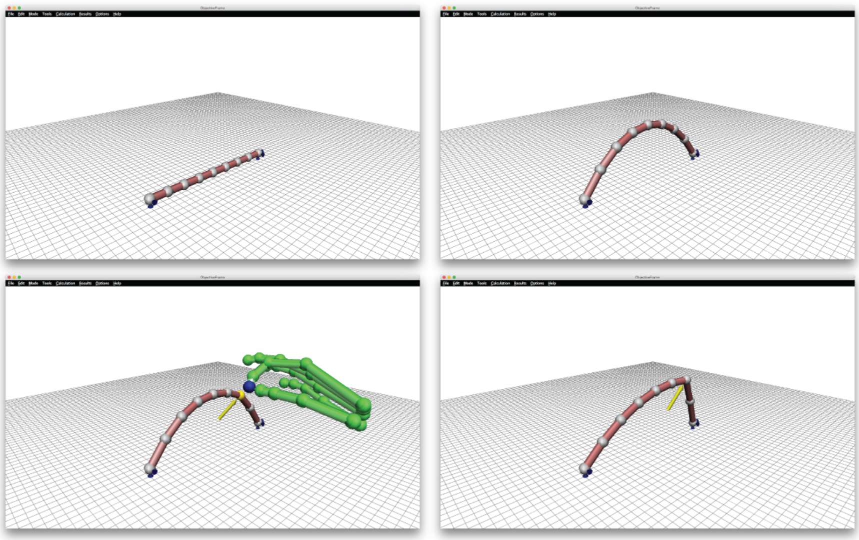

Figure 9: Educational example—the upper left image shows the initial geometry, and the upper right image shows the static equilibrium under a negative gravity load. In addition, the lower left image shows a point load being applied, and the lower right image shows the static equilibrium for a negative gravity load and point load.

As the designer applies a point load to the structure, the 3D dynamic response is interactively visualized. This can be used for educational purposes to improve the user’s understanding of the structural behavior of the model.

In Figure 10, an example is shown where the dynamic relaxation is used to find the form of a structure. The point load can here be used to move away from the optimal solution [38] in order to find other interesting sub optimal solutions that might be more aesthetically attractive to the designer. The point load can also, for example, represent a supporting column or a hanging installation in the structure.

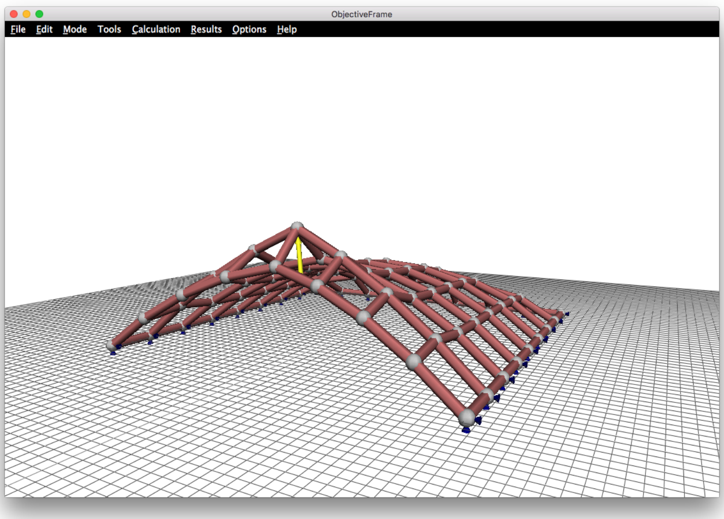

Figure 10: Example of a form-found structure using the developed application.

6 Discussion

This work shows that new 3D input devices have the potential to create very direct manipulation user interfaces for conceptual structural design, previously only achieved for 2D. The human-computer interaction in an existing application is improved, which improves the user’s ability to explore different designs. The conceptual design environment is important, and it can have a big impact on the final design. This work shows an alternative user interface for the development of such tools, which in the future could potentially have a big impact on how we design structures.

The implemented methods aim to improve the designer's understanding of both the static and dynamic behavior. The implemented methods also allow the designer to navigate the design space and balance structural performance and aesthetics.

Hand gestures are used in the application to manipulate the location and angle from which the structure is observed. This could easily be implemented in existing CAD software to allow the user to more easily navigate the 3D space.

6.1 Summary of intellectual contributions

- This paper includes critical review of existing tools and techniques for design manipulation in conceptual CAD.
- It is the first to propose very direct manipulation as human-computer interaction mode for 3D structures, thanks to a new type of 3D input device such as the Leap Motion Controller
- It introduces an implemented design tool that allows users to interact with 3D structures through very direct manipulation.
- It demonstrates potential applications through three case studies.

6.2 Future work

The Leap Motion Controller's SDK supports virtual reality glasses such as the Oculus Rift. Combining the two can create a virtual reality in which the user can experience the structure in 3D, interact, and make changes to it using his/her hands.

This could potentially be developed in a game environment where the structure could be visualized in its intended context, i.e., a building site. A game engine could enable real-time renderings of the structure in its context. The designer would then be able to make manipulations, guided by performance feedback, to the rendered structure. This could improve the conceptual design process, and by doing so, have a big impact on the design process and final structure.

6.3 Concluding remarks

- This study responds to need for new, more intuitive, and natural interaction modes in computational design and analysis
- Very direct manipulation significantly improves existing direct manipulation paradigms prevalent in CAD.
- New technologies like the Leap Motion Controller open up unprecedented possibilities for engaging users in the exploration and design of 3D structures, leading to improved understanding of design options and performance in the built environment.

7 Acknowledgements

This work was supported by the Swedish strategic research program eSSENCE. The author would also like to thank Jonas Lindemann for sharing the source code for ObjectiveFrame.

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